NEW STRUCTURE OF DUAL STATOR HYBRID EXCITATION FLUX SWITCHING MOTOR FOR AIRCRAFT APPLICATIONS

HASSAN ALI SOOMRO

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

STATUS CONFIRMATION FOR THESIS
DOCTOR OF PHILOSOPHY

NEW STRUCTURE OF DUAL STATOR HYBRID EXCITATION FLUX SWITCHING MOTOR FOR AIRCRAFT APPLICATIONS

ACADEMIC SESSION: 2020/2021

I, **HASSAN ALI SOOMRO,** agree to allow this Thesis to be kept at the Library under the following terms:

1. This Thesis is the property of Universiti Tun Hussein Onn Malaysia.
2. The library has the right to make copies for educational purposes only.
3. The library is allowed to make copies of this Thesis for educational exchange between higher educational institutions.
4. The library is allowed to make available full text access of the digital copy via the internet by Universiti Tun Hussein Onn Malaysia in downloadable format provided that the Thesis is not subject to an embargo. Should an embargo be in place, the digital copy will only be made available as set out above once the embargo has expired.
5. ** Please Mark (√)

☐	CONFIDENTIAL	(Contains information of high security or of great importance to Malaysia as STIPULATED under the OFFICIAL SECRETS ACT 1972) *Title and Abstract only*
☐	RESTRICTED	(Contains restricted information as determined by the Organisation/institution where research was conducted) *Title, Abstract and Introduction only*
		☐ EMBARGO _________ until_________ (date) (date)
√	FREE ACCESS	

Approved by,

____
(WRITER'S SIGNATURE)

____
(SUPERVISOR'S SIGNATURE)

Permanent Address:

H.NO. 06, VIP ROAD BHANGWAR COLONY, NAWABSHAH, SINDH, PAKISTAN.

Date: 09-02-2021

Supervisor's name

ASSOC. PROF. IR DR. ERWAN BIN SULAIMAN

Date: 09-02-2021

NOTE:

** If this Thesis is classified as CONFIDENTIAL or RESTRICTED. Please attach the letter from the relevant authority/organization stating reasons and duration for such classifications.

This thesis has been examined on 16th December 2020

and is sufficient in fulfilling the scope and quality for the purpose of awarding the Degree of Doctor of Philosophy in Electrical Engineering.

Chairman:

ASSOC. PROF. DR. SHAMSUL AIZAM BIN ZULKIFLI
Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

Examiners:

PROFESSOR IR. DR. HAZLIE BIN MOKHLIS
Department of Electrical Engineering, Faculty of Engineering
University of Malaya

ASSOC. PROF. DR. WAHYU MULYO UTOMOTS
Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

NEW STRUCTURE OF DUAL STATOR HYBRID EXCITATION FLUX SWITCHING MOTOR FOR AIRCRAFT APPLICATIONS

HASSAN ALI SOOMRO

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

FEBRUARY 2021

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged0

Student : ……………………………………………………
HASSAN ALI SOOMRO

Date : 09-02-2021……………………………………………………

Supervisor : ……………………………………………………
ASSOC. PROF. IR DR. ERWAN BIN SULAIMAN

Dedicated to
my beloved family,
my siblings and my friends
who always encouraged me with their love and prayers

ACKNOWLEDGEMENT

In the name of ALLAH, the Most Gracious and the Most Merciful. Alhamdulillah, all praises to Allah Almighty for His grace and His blessings given to me for the completion of my PhD studies successfully.

I also wish to express my gratitude to my supervisor, Assoc. Prof. Ir. Dr. Erwan Bin Sulaiman for his guidance, invaluable help, advice and patience on my project research. Without his constructive and critical comments, continuous encouragement and good humor while facing difficulties, I could not have completed this research. I am also very grateful to him for guiding me to think critically and independently.

I acknowledge, with many thanks, to Office for Research Management Centre (RMC) Universiti Tun Hussein Onn Malaysia and Ministry of Higher Education (MOHE), Malaysia for supporting me financially during my PhD program. I am much honoured to be the recipient for this award which motivates me to maintain a peaceful life and providing me confidence and willingness to achieve my goals.

Without support from technical staff and my lab fellows of flux switching machine (FSM) research group, this research would not have been undertaken. My sincerely thanks to all my FSM group friends who facilitated me every time with their technical knowledge.

It has been a very pleasant and enjoyable experience to work in UTHM with a group of highly dedicated people, who have always been willing to provide help, support and encouragement whenever needed. I would like to thank all my friends during my stay in UTHM. Life would never have been that exciting and joyful without you.

Finally, I would like to give sincere words to my parents for their endless love, support and for always making compromises to let me try whatever I consider is worth doing.

ABSTRACT

Aircraft applications demand high reliability, high torque and power densities while aiming to reduce weight, complexity, fuel consumption, costs, and environmental impact. New electric driven system such as flux switching machine (FSM) has been developed which is capable to meet these requirements as well as providing significant technical and economic improvements over conventional systems. However, FSMs with single stator associated with limited free space for active sources in stator, which leads to some drawbacks of complicated structure, less paths for flux flow, flux cancellations, and heat generation effects. To overcome these issues, FSMs using double stator (DS) have been proposed by many researchers which provide more free space for active sources and flux to flow. Whereas, these structures show some drawbacks of flux cancelations are saturations due to the arrangement of excitation sources in both stators. Therefore, this research presents design studies of new DS hybrid excitation FSM (DS HEFSMs) having permanent magnets (PMs) in inner stator while field excitation coil (FEC) and armature coils in outer stator so that coils can be easily inserted or replaced during fault conditions. Moreover, the performance analysis of proposed design is investigated and compared with existing DS designs based on 2D finite element analysis (FEA) using JMAG software ver. 16.0 In addition to obtain the optimum torque and power, proposed DS HEFSM is optimized by treating several design parameters defined in the rotor segments, armature slot, and FEC slot using deterministic optimization approach. Accordingly, the optimized design shows the capabilities to achieved 19.6% better flux linkage compared to initial design along with 38.67%, 30.58% and 2.91% increment in torque density, power density and in efficiency respectively. While, the torque and power achieved by final design are 17% and 58% more than existing PM synchronous motor (PMSM) respectively used for aircraft propeller applications. Finally, in this research it is concluded that the proposed DS HEFSM has shown the promising capabilities to achieve higher torque densities at maximum speed ranges and can be installed in various single seated aircrafts to fly at various altitudes.

ABSTRAK

Aplikasi pesawat memerlukan kebolehpercayaan yang tinggi, torsi tinggi dan ketumpatan daya yang tinggi, sambil bertujuan untuk mengurangkan berat badan, kerumitan, penggunaan bahan bakar, kos dan kesan persekitaran. Sistem pemacu elektrik baru telah dikembangkan, seperti Fluks penukar Mesin (FSM), yang dapat memenuhi keperluan ini dan memberikan peningkatan teknikal dan ekonomi yang signifikan berbanding dengan sistem mekanikal tradisional. Walau bagaimanapun, FSM dengan stator tunggal dikaitkan dengan ruang bebas terhad sumber aktiviti stator, yang membawa kepada beberapa kelemahan, iaitu, struktur kompleks, jalan fluks kurang, pembatalan fluks dan kesan penjanaan haba. Untuk mengatasi masalah ini, banyak penyelidik mencadangkan FSM menggunakan dual stator (DS), yang memberikan lebih banyak ruang kosong untuk sumber dan aliran aktif. Walau bagaimanapun, struktur ini menunjukkan beberapa kelemahan pembatalan fluks kerana ketepuan kerana penyusunan sumber pengujaan di kedua-dua stator. Oleh itu, penyelidikan ini menunjukkan kajian reka bentuk baru DS Hibrid angker FSM (DS HEFSM), yang stator dalamannya mempunyai PM, sementara FEC dan stator luaran mempunyai gegelung angker, sehingga gegelung dapat dengan mudah dimasukkan atau diganti sekiranya terjadi kegagalan. Di samping itu, analisis prestasi reka bentuk yang dicadangkan telah dikaji dan dibandingkan dengan reka bentuk DS yang ada menggunakan perisian 2D FEA. JMAG versi 16.0 Selain memperoleh daya kilas dan daya yang terbaik, DS HEFSM yang dicadangkan juga dioptimumkan dengan menggunakan kaedah pengoptimuman deterministik untuk memproses beberapa parameter reka bentuk yang ditentukan di bahagian pemutar, slot angker dan slot FEC. Oleh itu, reka bentuk yang dioptimumkan menunjukkan kemampuan untuk mencapai hubungan fluks 19.6% lebih baik daripada reka bentuk awal, dan ketumpatan tork, ketumpatan daya dan kecekapan masing-masing meningkat sebanyak 38.67%, 30.58% dan 2.91%. Pada masa yang sama, tork dan daya yang diperoleh dengan reka bentuk akhir adalah 17% dan 58% lebih tinggi daripada PMSM yang ada yang digunakan dalam aplikasi pesawat. Akhirnya, kesimpulan yang dibuat dalam kajian ini adalah

bahawa HEFSM DS yang dicadangkan telah menunjukkan ciri-ciri yang menjanjikan untuk mencapai kepadatan tork yang lebih tinggi dalam julat kelajuan maksimum dan dapat dipasang dalam pelbagai aplikasi dalam pesawat satu tempat duduk.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A_g	-	Air gap
A_w	-	Area of wire
α	-	Filling factor
B	-	Magnetic field
E_B	-	Bottom end coil length
E_{ind}	-	The voltage induced in the turn of the coil
E_T	-	Top end coil length
e_k	-	Phase back-emf
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
I_a	-	Armature coil current
I_e	-	Field excitation coil current
J_a	-	Armature current density
J_e	-	Field current density
L	-	Length of 1 turn
L_{si}	-	Circumference of inner stator
η	-	Efficiency
N	-	Number of turns of wire in coil
N_{cte}	-	Electrical angle of rotation for each period of cogging torque
N_{ctp}	-	Number of periods
N_e	-	Number of FE coils
N_r	-	Number of rotor poles
N_s	-	Number of stator slots
n_s	-	Rotational speed in revolution per minute
P	-	Instantaneous power
P_{ac}	-	Armature coil copper loss

P_c	-	Copper loss
P_{fec}	-	FEC copper loss
P_i	-	Iron loss
P_o	-	Output power
P_r	-	Rotor iron loss
P_s	-	Stator iron loss
R	-	Resistance
r_{ir}	-	Inner radius of rotor
r_{or}	-	Outer radius of rotor
r_{sbi}	-	Radius of stator back inner
r_{si}	-	Inner radius of stator
r_{so}	-	Outer radius of stator
S_e	-	FEC slot area
S_a	-	Armature coil slot area
t	-	Time
T_e	-	Electromagnetic torque
T_{rel}	-	Reluctance torque
T_{exc}	-	Excitation torque
w_r	-	Rotor tooth width
w_s	-	Stator tooth width
ω_r	-	Rotational speed in radian per second
θ	-	Electrical angular position of rotor
θ_{seg}	-	Segmental rotor span
ρ	-	Copper resistivity
φ	-	Flux
Ψ_{exc}	-	Flux linkage due to field excitation
AFPMSM	-	Axial flux permanent magnet machine
CGA	-	Conjugate gradient algorithm
CNC	-	Computer numerical control
DC	-	Direct current
DE	-	Differential evolution
DFDSM	-	Doubly fed dual stator motor
DOA	-	Deterministic optimization approach

DS	-	Dual stator
EV	-	Electric vehicle
FE	-	Field excitation
FEA	-	Finite element analysis
FEFSM	-	Field excitation flux switching motor
FEM	-	Finite element method
FEC	-	Field excitation coil
FSM	-	Flux switching motor
HCF	-	Highest common factor
HE	-	Hybrid excitation
HEFSM	-	Hybrid excitation flux switching motor
IM	-	Induction motor
IPMSM	-	Interior permanent magnet synchronous motor
Nd	-	Neodymium
PM	-	Permanent magnet
PMFSM	-	Permanent magnet flux switching motor
PMSG	-	Permanent magnet synchronous generator
PMSM	-	Permanent magnet synchronous motor
RFPMSM	-	Radial field permanent magnet synchronous motor
RaDS	-	Radial field dual stator
SQP	-	Sequential quadratic programming
SRM	-	Switched reluctance motors
THD	-	Total harmonic distortion

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Inflight passenger transportation has been growing annually at the rate of 9% since 1960s, and has bring the world nearer to the global warming. While, currently air transportation remains costly and yields 2% of artificial corban dioxide emissions. As a result, both the aircraft operators and the aerospace industry are projected to offer continuous improvements in terms of safety, capability, reliability and availability while reducing costs, noise, and CO_2 emissions. To meet these expectations, aerospace systems are undergoing a long-term transition from using mechanical, hydraulic, and pneumatic power systems toward globally optimized electrical systems[1-2].

Electric motor drives are capable of converting electrical power to drive actuators, pumps, compressors, and other subsystems at variable speeds used in conjunction with advanced power electronics and control strategies in aircraft applications. Beside, electric drives can offer gains in overall efficiency, weight saving, and cost effectiveness, while meeting reliability requirements. In addition, electrical machines providing high torque density are prominent for the viability of direct-drive electrical propulsion of aircraft applications [3-5].

To date, brushless flux-switching motors (FSM) machines have attracted imperious interest as a candidate machine technology for applications requiring high torque density, fault tolerance, high efficiency and robust rotors [6]. FSMs are also well suited to high-speed applications since the active sources such that permanent magnet (PM) and field excitation (FE) are located on the stator, leaving rotor structure robust [7-8]. Mainly, FSMs can be categorized into three types by the nature of their excitation used, such that permanent magnet (PM) FSM, (FE) FSM and hybrid excitation (HE) FSM. In PMFSM and FEFSM main excitation sources used are PM and FE correspondingly, while both PM and EF are combined to generate flux in HEFSM [9].

Due to the advancement of modern high-performance rare earth magnetic materials, PMFSMs are being increasingly more popular in various applications, ranging from electric and hybrid electric vehicles, renewable energy systems including wind power generators, electric aircrafts, industrial drives, automations, to domestic appliances. [10].

In the literature, up to now various successful topologies of PMFSMs structures have been introduced and designed to enhance the performance. Recently, the research of dual-stator (DS) PM machines have received much attention [11]. Dual-stator machine is a motor which consist of an inner machine and an outer machine, aiming to improve the torque density and efficiency of machine. A lot of researches have shown that the DS-PMFSM makes full use of the inner space to enhance the performance. In [12] a novel DS 6/4 PMFS machine has been proposed to eliminate the second-order and other even harmonics in the flux linkage and produce symmetric and sinusoidal back-EMF. Hence DS-PMFSMs can achieve higher torque in the same volume and improve the utilization ratio of material and space [13-14].

Benefiting from the high performance of rare earth magnet motors, such as high efficiency, high torque density, and compactness, there is potential for extensive diminution of rare earth magnet resources [15]. Though, in recent years, the price of rare earth materials, such as neodymium and dysprosium, are dramatically increased, i.e. the cost of PMs could be half of the cost of an entire motor. Therefore, the development of high-performance electric motors with less or no rare earth magnets becomes an important research direction [16-17].

Alternatively, in recent DS-FEFSMs have been proposed and analysed. In DS-FEFS machine the armature and field windings are separately housed in the outer and inner stator respectively to avoid overlapping and hence reduce copper losses [18]. More importantly, The DS-FEFS machine combine flexible flux regulation with low cost of production, but it sacrifice torque density and efficiency due to less flux strengthening [19].

Therefore, the concept of DS hybrid excited (HE) machines, in which PM and DC excitations coexist, is proposed to combine their advantages. DS HE machines are best candidates for variable-speed applications, e.g. electric vehicle, aircraft and wind power generation etc. [20-21]. The topologies of DS HE machines are diverse, as two excitation sources can be arranged flexibly. A multitude of novel DS structures have been proposed and investigated in the past two decades. According to the connection type between FE and PM Field, the HE machines are divided into two groups, i.e. series HE and parallel HE topologies. For series HE machines, the flux created by the field coils would go through PMs. Thus PM and field winding have the same flux path [22]. In parallel HE machines, the PM excitation and field excitation have independent magnetic flux path. Compared with the parallel structure, the series HE machines have much more simple structure. But there are some disadvantages of poor field strengthening and demagnetizing of PMs for these machines. In parallel hybrid excitation machines, the PM is not in the magnetic circuit of the excitation coils. The excitation coils are not only used for the field-weakening but also for the field-strengthening. The excitation current is much smaller because of the lower magnetic reluctance [23].

1.2 Problem Statements

In order to improve the torque and power density, dual stator DS PM machines are developed by utilizing the inner space, such as DS 'rotor-PM' and 'DS-PMFS machines' [24-25]. Nevertheless, PM machines have some drawbacks, such as high price of rare earth material, relatively lower flux-weakening capability, uncontrollable flux, demagnetization and limited working temperature [26]. Therefore, non-PM machines have become one of the most popular research topics. In [18], FEFSM machine has been proposed and analysed with double stator. However, it draws more copper losses as both the armature and field windings are separately accommodated on the outer and inner stators. It also sacrifice torque density and efficiency due to less flux strengthening capabilities.

Therefore, the concept of dual stator DS (HE) machine, in which PM and FE coexist, is proposed to combine their advantages [27]. A multitude of dual rotor structures have been proposed and investigated in the past decade.

Conventional DS HEFS machines are shown in Figure 1.1. There are certain issues in DS HEFSMs such as, PMs and FE coils are located in the inner stator in case of Figure 1.1 (a) and Figure 1.1(b), hence PMs and FEC fluxes have to flow in same magnetic path. Therefore, due to the low permeability of the PMs, the magnetic reluctance of the magnetic path for excitation coil is quite high which cause the degrading of flux regulation effect along with high risk of irreversible demagnetization [28-29]. Besides, presence of FEC in inner stator provide difficulty to inject supply currents in both machines. Moreover, during fault condition or maintenance it's also difficult to replace the coil or damaged PMs. On the other hand, in case of Figure 1.1(c) both armature and FE coils are wounded on each tooth of the outer stator which increases the copper losses and heating effects on outer stator [30]. In Figure 1.1(c) PMs are located in the inner stator in circumferential directions and makes the stator in twelve different parts and hence decrease the strength of the structure to be used for high speed applications [31].

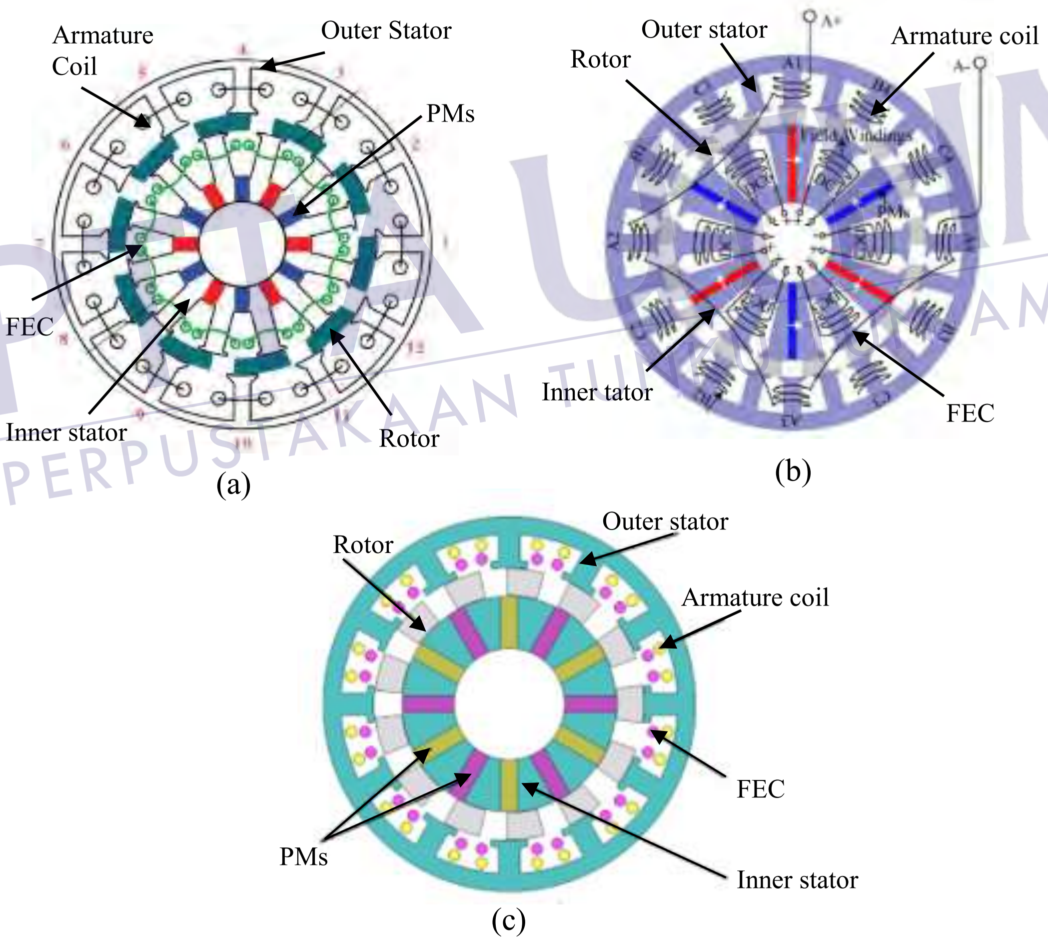


Figure 1.1: Conventional structures of DS HEFSMs

Therefore, taking full account of aforementioned issues, a novel topology of DS HEFSM is proposed to comprehensively improve the motor performance including torque density, efficiency, and torque pulsations. The proposed structure realizes the

HE of magnetic path with relatively considerable simple and compact structure due to the arrangement of both excitation sources in separate stators. Unlike existing DS HEFSMs, the armature coils and FECs are arranged on outer stator separately for easy maintenance in case of fault, easy cooling and easy to inject field current in FE coil for field regulation to realize field control. Furthermore, two stators improve reliability, flexibility, fault tolerance capability and torque density due to higher useful electromagnetic space.

1.3 Objectives of the study

The main objective of this study is to develop a new structure of DS HEFSM for aircraft applications. To achieve the main objective, there are some specific objectives that have to be fulfilled, which are:

(i). To analyse various topologies of DS HEFSMs using same dimensions for flux linkages and torque performance.

(ii). To design and compare the performance of proposed DS HEFSM with various DS HEFSMs under several armature coil conditions and field current densities for induced EMF, cogging torque, average torque power and efficiency performances.

(iii). To optimize the proposed DS HEFSM using deterministic optimization approach for optimum performances.

1.4 Scope of Works

The scope of this research is highlighted in the following points. Whereas, to conduct the research, commercial FEA package, JMAG-Designer ver.16.0 released by Japan Research Institute (JRI) is used as a 2D-FEA solver for the design of proposed and various DS HEFSM. The proposed DS HEFSM structure is designed following IEC standard (IEC 60034-1) which is (Rotating electrical machines – Part 1: Rating and performance) [32].

(i). Initially, a coil test analysis was performed for feasible topologies of DS HEFSM to confirm the operating principle of proposed DS HEFSM.

(ii). The limit of the current density was set to the maximum at $15A_{rms}/mm^2$ for armature winding and 15 A/mm^2 for FEC respectively. Which is similar as permanent magnet synchronous motor (PMSM) presented in [33-34] for propeller of “Lange Antares 20E” one-seater aircraft developed by Lange Aviation (Germany) along with same outer diameter, stack length and PM weight following the IEC standard “IEC 60034-22:2009”. Whereas, the design parameters and specification of PMSM for propeller of “Lange Antares 20E” one-seater aircraft are presented in Table 1.1.

(iii). The electromagnetic performance of proposed DS HEFSM, including induced EMF, cogging torque, and average torque is analysed and compared with various DS HEFSMs using 2D-FEA. The torque-speed characteristics were evaluated by varying the armature phase angle, θ.

(iv). The iron and copper losses calculation is based on 2D-FEA and formula, which assisted in calculating the efficiency of the proposed DS HEFSM.

(v). Deterministic optimization approach (DOA) is used to achieve optimum average torque and power for proposed DS HEFSM. The outer diameter of outer stator, the motor stack length, the shaft radius, and the air gap, having dimensions 273 mm, 91 mm, 30 mm and 0.5 mm, respectively, are kept constant during the various cycles of optimization.

Table 1.1: Design restrictions and parameters of PMSM used in [34]

Items	Units	PMSM
Outer stator diameter (D_{os})	(mm)	273
Inner stator diameter (D_{is})	(mm)	-
Rotor outer diameter (D_{ro})	(mm)	160
Rotor inner diameter (D_{ri})	(mm)	120
Motor stack length (L_{st})	(mm)	91
Air gap length (L_{ag})	(mm)	0.5
Shaft diameter (D_{shaft})	(mm)	120
PM weight (W_{pm})	(kg)	2.8
Maximum armature current density (J_a)	(A_{rms}/mm^2)	15
Maximum field current density (J_e)	(A/mm^2)	15
Number of turns (N)	-	11

1.5 Thesis Outlines

This thesis deals with the design investigation, comparison and optimization of new DS HEFSM. Mainly, this thesis is divided in to five chapters and the summary of each chapter is given below.

(a) Introduction

The first chapter introduces the background of the research, importance of FSMs and the explanation regarding problems associated with existing double DS FSMs. Along with research objectives and scope of the research are discussed in this chapter.

(b) Literature Review

This chapter explains the literature of electrical motor and classification of electrical motor including flux switching motors. The study design and analysis of various existing DS FSMs and critical review are discussed in this chapter. Moreover, literature on optimization is also highlighted in this chapter.

(c) Methodology

This chapter describes the project implementation of this research. The project implementation is divided into three parts including analysis of various DS HEFSMs in terms of flux linkage, secondly, design and performance comparison of proposed DS HEFSM with others DS HEFSMs, and thirdly, process of optimization using (DOA) to obtain optimum torque and power performances.

(d) Results and analysis

This chapter comprises of outcomes of the research including design investigation, performance analysis and optimization process. Initially, the design investigation and performance comparison of various DS HEFSMs have been presented on the basis of FEA. Moreover, a new design of DS HEFSM structure is proposed and the analysis of DS HEFSM is compared with other DS designs. Besides, the optimization process of DS HEFSM is discussed to enhance the performance of the proposed DS HEFSM. Finally, the performances of optimized designs are compared with initial design of DS HEFSM and it is found that the optimized design has successfully achieved the target performance.

(e) Conclusion

The final chapter describes and concludes the summary of the research and the comparison of analysis of the research with previous work. Also the suggestions of future work are described in this chapter.

CHAPTER 2

ELECTRIC MACHINES: A REVIEW

This chapter reviews the types of rotating electric machine based on the principle of flux switching for aircraft applications. Flux switching mechanisms of various FSMs are explained, from the early concepts to the modern designs. Merits and demerits of various FSMs with dual stator are highlighted and numerous approaches are discussed to evaluate their performances.

2.1 Overview of electric motor

Electrical motors are significant component in any electrical drive system where aerospace applications place specific requirements for reliability and power density on the electrical machine employed. In view of machine design for safety-critical applications, the criteria that should be satisfied are, high torque/weight ratio, high value of the phase inductance and high efficiency throughout the full speed range while, electrical machines with brushes or commutators are not considered because of their high maintenance requirements, low torque density, and lack of reliability [35-37]. However, in recent years there have been a lot of researches and new inventions on electric brushless machines in which the magnets are mounted on the stator. These machines are categorised as stator-PM machines. The electric machines with PM on the stator have two advantages, the first is temperature rise is easily managed and the second one is that PM is not subjected to the centrifugal forces of rotating rotor [38-40]. Among the stator-PM machines that has recently become an attractive research topic is the flux switching machine (FSM). In general, the FSMs are doubly salient in which the rotor position determines the path of excitation flux on the stator, then flux coupling with the stator coil.

2.2 Overview of Flux switching motors

In 1952, the first single-phase FSM was introduced by A. E. Laws having four stator slots and four rotor poles [41]. The basic principle of FSM discussed in [42-43], wherein motor comprises of stator windings pair, two laminated yolks, and PMs situated on the stator, whereas the rotor has only two salient poles mounted to the shaft. In 1997 Poly phase motor was first reported using the FSM principle by E. Hoang et al. [44]. Since then, numerous novel FSM designs have been established for various applications, such as in automotive drive system, wind power generators and aerospace industries. Due to bipolar flux-linkage characteristics, FSMs have been seen as most suitable applicant for aircraft applications [45-49].

Moreover, similar to certain other conventional machines, the FSMs adapt the inner-rotor and the outer-stator configuration for most the applications [50-52]. With such a traditional topology, both PM materials and the armature windings are placed in the outer stator. Mainly, the FSMs are categorized into three types that are PMFSM, FEFSM, and HEFSM. PMFSM and FEFSM use only PM and field excitation coil (FEC), respectively as their main flux sources, whereas, HEFSM combines both PM and FEC as their main flux sources.

2.2.1 Permanent Magnet flux switching machines (PMFSMs)

Firstly, a three-phase PMFS machine functioning prototype was introduced in 1997 by E. Hoang [53]. Since then, for different applications, several innovative designs have been developed to improve reliability whether in terms of torque and power, high speed or motor efficiency. Figure 2.1(a) shows a standard three-phase 12S-10P PMFS machine wherein the stator comprises of "concentrated armature winding" wounded on both tooth of stator. A PM was positioned in between the "U-shaped" segments and the polarity of PM was switched from one to another magnet [54]. Alternate winding poles were examined for three-phase PMFSM to be tolerant to fault as shown in Figure 2.1(b). Though, these type of PMFS machines have the drawbacks of large amount magnet which can cause to increase the weight and cost of the machine. Henceforth, a new configuration of E-core PMFS machine was developed to minimize the volume of PM by simply converting the alternate wound pole in to a simple stator tooth, as shown in Figure 2.1(c) [55]. In addition, the stator tooth was extracted to widen the area of slots which help to improve the characteristics of E-core PMFSM, thus the "C-core PMFSM" was established, as explained in Figure 2.1(d).

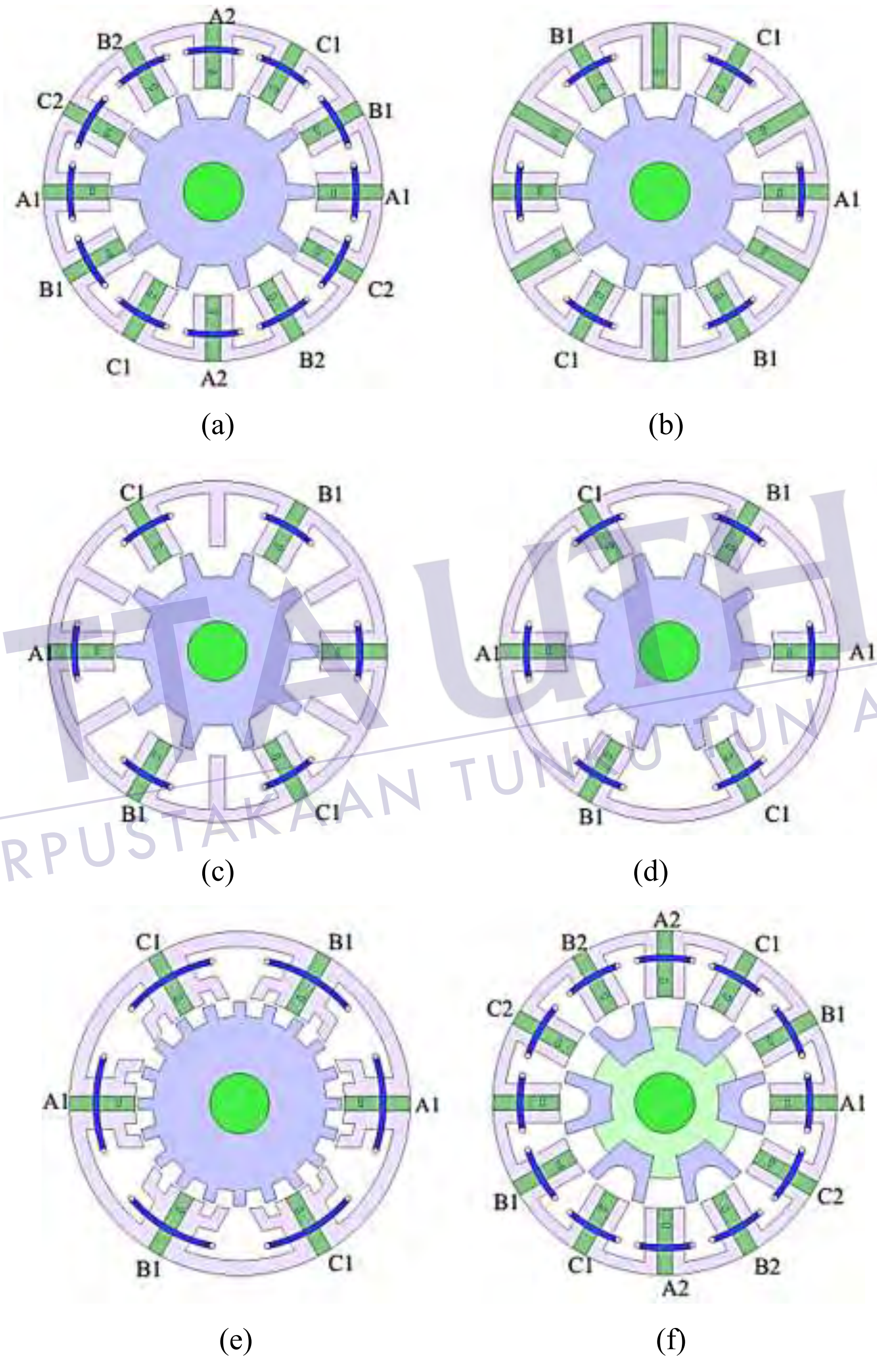


Figure 2.1: PMFSM topologies. (a) 12S-10P PMFSM each pole wounded (b) PMFSM alternative poles wound (c) E-core PMFSM (d) C-core PMFSM (e) Multi-tooth PMFSM (f) Segmented rotor PMFSM [54-56]

Alternatively, the configuration of a new “multi-tooth PMFSM” described in [56], has been used to improve torque density and minimize PM volume use, as shown in Figure 2.1(e). A three-phase PMFSM using segmented rotor has also been published, as can be seen in Figure 2.1(f). Such types of machines had lesser robust framework, which should be acknowledged if used for high-speed applications.

2.2.2 Field excitation flux switching machines (FEFSMs)

The PM excitation on traditional PMFSM stator can easily be substituted by DC FEC as seen in Figure 2.2 to develop field excitation flux switching machine (FEFSM). The FEFSM is a type novel topology of "salient- reluctance machine" which, combines the principles of "inductor generator” and “SRMs” [57-59]. The FEFSM principle contains exchanging the flux polarity of the armature, coil with respect to the position of the rotor. Figure 2.2(a) demonstrates the models of early single-phase 4S-2P FEFSM deploying the stator with a FEC winding, a toothed rotor and maximum pitched windings on the stator [60]. It is evident from the figure that two armature coils and FE coils were positioned in the stator that overlapped one another. Another example of a single-phase FEFSM with 8 slots 4 rotor poles [61], is shown in Figure 2.2(b). From the figure, FEC winding is fed with direct current in four of the slots to create four pole magnetic fields. The remaining four slots also comprise an armature winding pitched over two stator teeth. The current direction in the armature coil determines the flux and position of the rotor in four stator poles. While, the FE coil is energized by unipolar current, which can be associated directly in parallel or in series with the DC power converter, to feeds the bipolar current into the armature coil. The principle of design was discussed in [62], and the single-phase 8S-4P FEFSM reached high power density than the “induction motor”. The three-phase 12S-10P and 12S-8P FE-FSMs are designed to boost the efficiency of the single-phase FEFSM as shown in Figure 2.2(c) and (d), correspondingly.

The FEFSM 12S-10P in Figure 2.2(c) is modified from the PMFSM 12S-10P in Figure 2.2(a). Where the PM is eliminated from the stator, and half of the upper layer armature coil slots are mounted with the FEC windings as stated in [63]. The FEC-1 and FEC-2 are combined with alternate DC current source to create two flux polarities, identical to the 12S-10P PMFSM polarity discussed in Figure 2.2(a).

However, because of the separated and unused stator teeth shown as red circles in Figure.2.2(c) reduced the machine efficiency, which lead to the further observations should be conducted to improve the machine design of three phase FEFSMs.

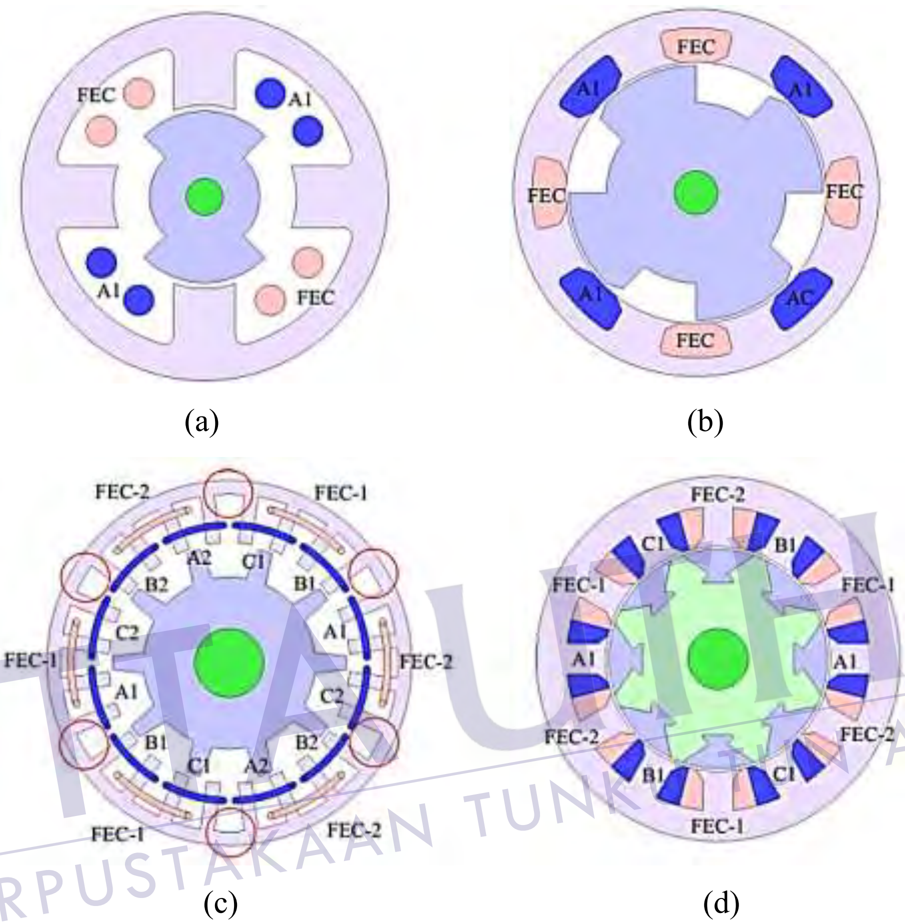


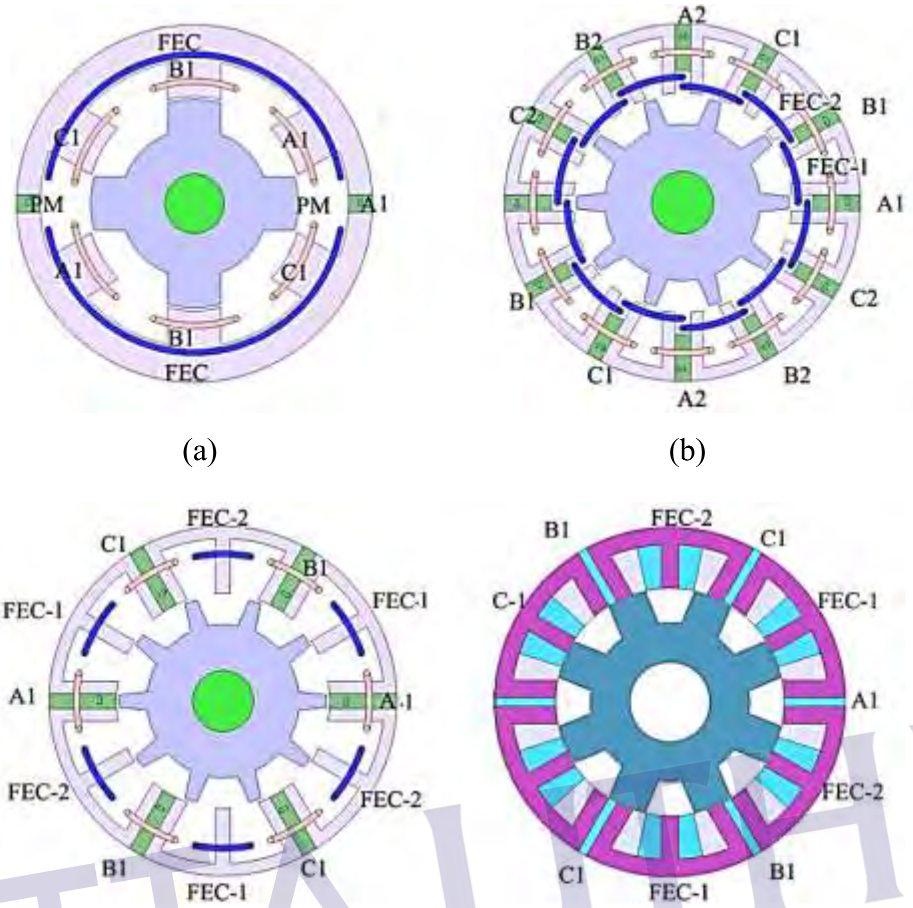
Figure 2.2: Topologies of FEFSMs (a) 1-phase 4S-2P FEFSM (b) 1-phase 8S-4P FEFSM (c) 3-phase 24S-10P FEFSM (d) 3-phase 12S-8P segmented rotor FEFSM [60-63]

Finally, the 12S-8P FEFSM is designed using the conflagration of segmental rotor as depicted in Figure 2.2(d) [64]. While, the segmental rotors structures are conventionally applied in the “synchronous reluctance machines (SynRM)”, the key role of the segments in the proposed machine is to deliver a specified magnetic pathway for transmitting the field flux to alternate armature coils as rotor revolves. This arrangement provides shorter end windings than the configuration of a toothed rotor connected with overlapping coils. This method has major advantages as it uses less conductive materials and can also increase the overall motor performance [65].

2.2.3 Hybrid excitation flux switching machines (HEFSMs)

HEFSMs use two flux sources for excitation, that are PMs and FECs as depicted in Figure 2.3 [66-67]. These machines with double excitation sources have been extensively studied for several years and have the ability to offer higher torque and power densities, higher efficiency and adjustable flux capacity [68-71]. A 6S-4P HEFSM is presented in Figure 2.3(a), which comprises of field winding, armature winding, and PMs, organized in three layers in the stator. Nevertheless, this design provided long-end DC windings, which raised the loss of copper and limited the efficiency. A novel 12S-10P HEFSM has been addressed in [67], wherein the PM was positioned between the stator segments providing ample space for FEC as shown in Figure 2.3 (b). HEFSM's capability for flux control can be regulated by changing the PM dimensions in radial position. The new E-core HEFSM configuration employing non-overlapping winding of DC field and armature coil is presented in [71] as shown in Figure 2.3(c).

The slot area was identical with same number of turns for both the FEC and armature winding. Three phase E-core HEFSM with non-overlap windings and decreased PM volume, as shown in Figure 2.3(d), has recently been evaluated in [72]. The reliability of the E- core HEFSM was also investigated in terms of flux strength, torque, and power vs. speed curves. The machine being developed prides itself on the merits of reduced cost and less copper. However, these machines with single stator are associated with limited free space for active sources in stator side, which leads to various drawbacks of complex structure, less space for flux to flow, flux cancellations, heat generation and demagnetizing effects. Therefore, the most common approach to enhance the torque density for propulsion applications is the use of high-speed outer-rotor motors with mechanical gears. The use of mechanical gear, however, results in a decrease in drive output and creates additional problems with mechanical gear lubrication, cooling and maintenance [73]. Henceforth, the implementation of two motors mounted on a common shaft proposed in article [74] for the direct drive. The combination of these two motors can be a double-air gap single motor.



(a) (b) (c) (d)

Figure 2.3: Topologies of HEFSMs (a) 6S-4P (b) Three-phase 12S-10P (c) 12S-10P E-core (d) 6S-8Pole E-core [66, 67, 71, 72]

The dual air gap motor can be grouped into two categories, such as the dual stator motor [75-77] and the dual rotor motor [78-79]. This motor looks very convenient for various high torque density applications. It has higher density of power, and torque. The double stators further increase the reliability and failure-safe ability to function. Additionally, the two stators potentially enable more methods to reduce torque ripples [80-82].

2.3 Double stator electric machines

In conjunction with FSMs, many other double stator electric motors have been found with their distinct advantages and drawbacks such as double stator Switch Reluctance Machines (DS-SRMs), DS Induction Machines (IMs), DS DC machines (DS-DCMs) and DS Permanent Magnet Synchronous Machines (DS-PMSMs) as shown in Figure 2.4. Where, induction machines provide relatively low cost, higher reliability, easy to maintain, and reliable structure which can be used in driving systems electric vehicle [83-84]. However, induction machine (IM) drawbacks involve lower power factor, higher losses, low inverter-use factor, and less efficiency. Thus, induction machines are not suitable for electric propulsion system to be used for aircraft applications [85-86].

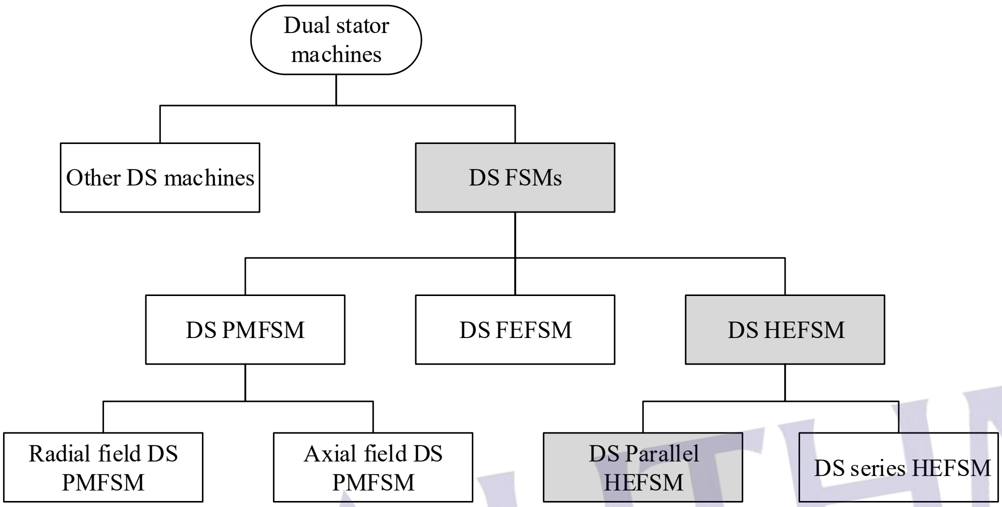


Figure 2.4: Overview of DS Machines

On the other hand, DS DC machines are widely used because it's high efficiency and simple control. DS DC machines give the advantages of simple structures and simple control in terms of the airgap flux and armature coil current, hence torque can be controlled independently. Nevertheless, due to usage of commutators and brushes DS DC motors suffer to be used for high torque applications [87]. Moreover, such machines often require large structure, with less efficiency and low reliability. Because of all these characteristics DS DC machines are inappropriate for aircraft applications [88].

In addition, DS SRMs are among the viable choices and have certain benefits, like low-cost, simple structural configuration, simple magnetic arrangement and rotor free from PMs, hence provide the high torque density [89]. However, DS SRMs have some drawbacks such as complex control is required as compared to IMs and DC motors, high acoustic noise due to nonlinear electromagnetic behaviour, and high torque ripples. Besides, the low efficiency and power density output represents a big downside compared to DS PMSMs [90-91].

Furthermore, DS PMSMs provide a high torque and increased efficiency yet they have demagnetization demerit, a complicated structure that is challenging to optimize together with a cost of PMs [92-94].

In recent, among the "stator PM" machines which have acquired significant interest from the researchers is the "flux switching machine (FSM)". FSM has dual salient configuration as well as its position of rotor defines the flux path of excitation on the stator, which results effective flux linking with the stator coil [95-96].

2.3.1 DS Permanent Magnet flux switching machines (DS PMFSMs)

The DS PMFSMs can be applied to a wide variety of applications. DS PMFSM's capability of producing higher torque density and effectiveness are significantly better than conventional permanent magnet synchronous machines. Though, there are many innovative structures of PMFSMs having various stator slots and rotor poles arrangements are established in the literature. The research mainly focuses on two types of DS PMFSMs, which are radial DS PMFSM and axial DS PMSM. From the literature, Radial DS PMFSM machines have received much attention hence various successful topologies of RaDS FSMs structures using PM excitations have been introduced and designed to enhance the performance for various applications. Ra DS PMFSM machines have been developed by utilizing the inner space, in order to improve the torque density.

2.3.1.1 Radial field DS PMFSMs

In 2014, a new type of RaDS PMFS machine had been examined to conduct a comparison with the existing conventional permanent magnet synchronous machine (DSPMSM) in [97]. The transient and steady state electromagnetic performances of the machine were conducted in details using finite element analysis (FEA). Figure 2.5 shows proposed stator-PM DS-PMFS motor. In this structure simply doubly salient rotor is implemented along with two stators. As there is absence of PMs and coils in the rotor side, the projected RaDS-PMFSM provides significant configuration [97]. The RaDS PMFSM delivers high flux density in the air gap, higher torque and efficiency at the same current density when compared with (DS-PMSM). However, this structure also provides higher values in terms of cogging torque, which will show the unwanted situations for the high speed applications.

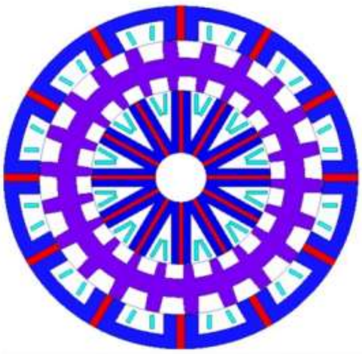
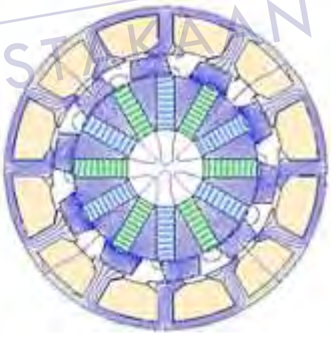
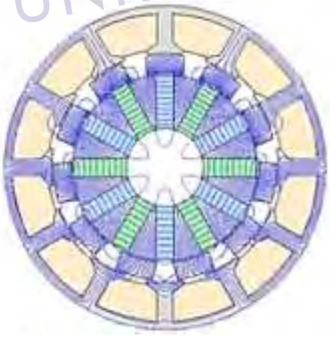


Figure 2.5: 12/22 radial field DS PMFSM [97]

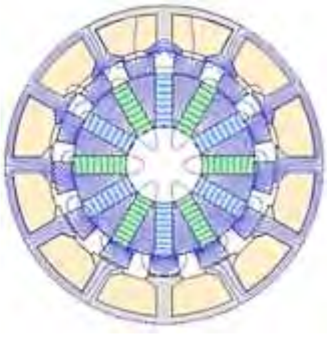
Whereas in 2015, another example of RaDS PMFS machine was presented which consists of a traditional FSM without PMs in the outer stator while, PMs are located in an inner stator along with a salient rotor in between both stator as shown in Figure 2.6. This new design connects two different machines in one design, which are "magnetically geared" and "switched flux machines". The double stator "switched flux machine" has been optimized using different numbers of rotor poles such as (10, 11, 13, and 14) and the performance of this machine is analysed at four different numbers of rotor poles by means of FEA method [98].



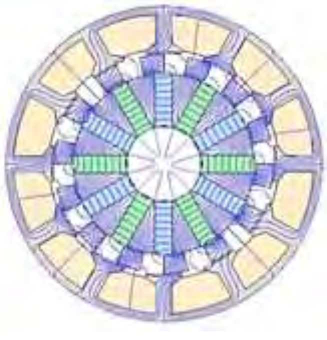
(a)



(b)



(c)



(d)

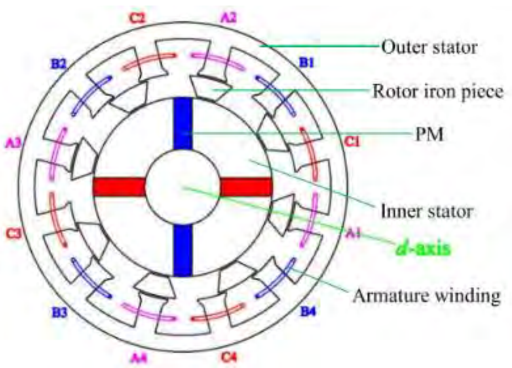
Figure 2.6: DS-PMFSM at (a) 10 pole, (b) 11pole, (c) 13 pole, (d) 14 pole [98]

Moreover, torque ripples as well as electromagnetic torque were also examined. It was found that the maximum rated torque was generated by the machine having 11 rotor poles. Whereas, minimum cogging and on-load torque ripples found in the machine having odd numbers of rotor poles. However, machines having 10 rotor poles and 14 rotor poles show unbalanced back EMF [98]. Table 2.1 shows the cogging torque, back emf and average torque performances of the Ra DS PMFS machine [98] with different number of rotor poles. From the table it is obvious that the Ra DS PMFS machine with 11 number of poles attained the higher torque.

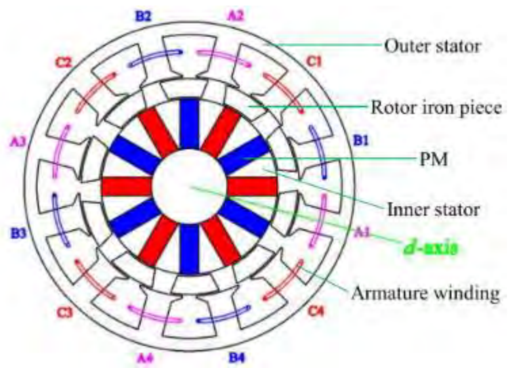
Further in the same year 2015, a novel “double stator doubly salient permanent magnet” (DS-DSPM) machine having separate excitation sources of PMs and armature coils were suggested in [99]. Similar to the single stator “conventional DSPM machines” wherein PMs are mounted in the yoke and windings are settled on the teeth. Two sets of DS-DSPM machines were suggested, i.e. DS-DSPM-I and PS-DSPM-II, based on the standard DSPM-I and DSPM-II machines which comprises of the PMs which are situated on the yoke of the stator [99] as shown in Figure 2.7.

Table 2.1: Performance of Ra DS PMFSM [98]

Reference	Ra DS PMFSM [71]			
Rotor poles	10	11	13	14
Back emf (V)	6.3	6	5.75	4.45
Cogging torque (Nm)	0.025	0.024	0.021	0.15
Torque (Nm)	6.65	7.85	7.8	6.2



(a)

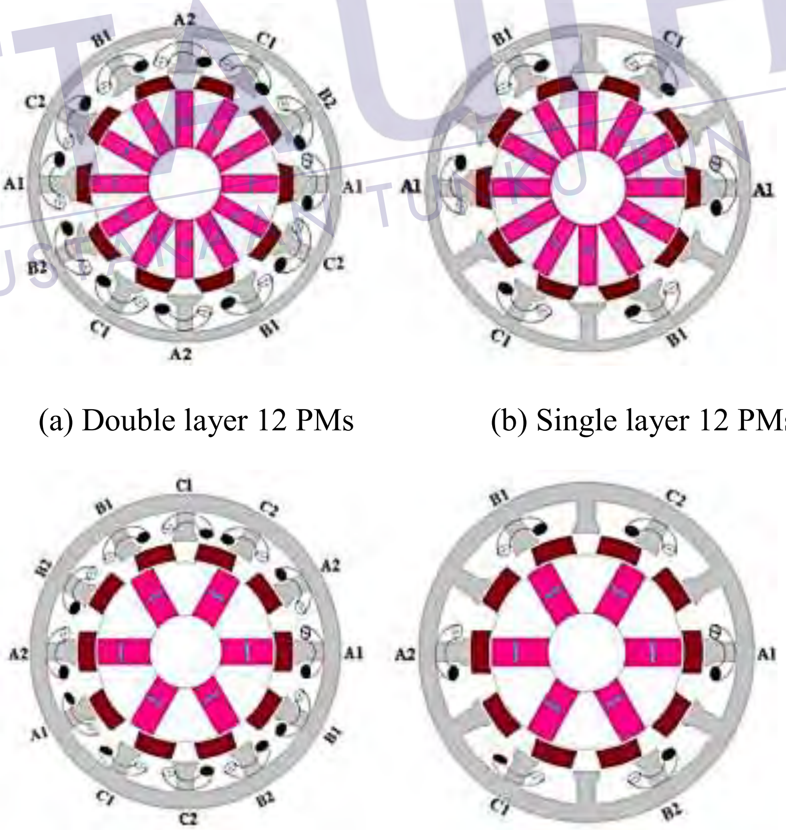


(b)

Figure 2.7: Cross section view of (a) 12S/8P DS-DSPM-I machines (b) 12S/10P DS-DSPM-II machine [99]

The overall performance of the proposed DS-DSPM machines such as back electromotive force (EMF) torque and power densities were investigated and compared with conventional DSPM machines on the basis of optimal designs for the maximum average torque and power using FEA in [99]. The investigation results that the suggested “DS-DSPM-I” and “DS-DSPM-II” machines have the capability of producing 8.49% and 207% higher torque densities than the “conventional DSPM-I” and “DSPM-II machines” with equal copper losses correspondingly. A prototype of “PS-DSPM-II” is established and verified to with the FEA results.

Moreover again in 2015, the performance of another (DS-PMFS) machine with “single-and double-layer windings” were presented and it was compared when the internal stator was designed with the same number or half the number of PMs as that of the outer stator teeth in [100]. The overall performance of proposed machines were inspected using FEA method. The main difference between the design of DS-PMFS machines in Figures 2.8(a), 2.8(b) and Figures. 2.8(c), 2.8(d) is that in the former two DS- PMFS machines, the inner stator is equipped with the identical number of PMs as that of the outer stator teeth, whilst in the latter two DS-PMFS machines the inner stator is equipped with half the number of PMs as that of the outer stator teeth.



(a) Double layer 12 PMs (b) Single layer 12 PMs

(c) Double layer 6 PMs (d) Single layer 6 PMs

Figure 2.8: Cross-sectional diagrams of the l2S-10P DS-PMFSMs for single and double-layers windings with 12 and 6 PMs [100]

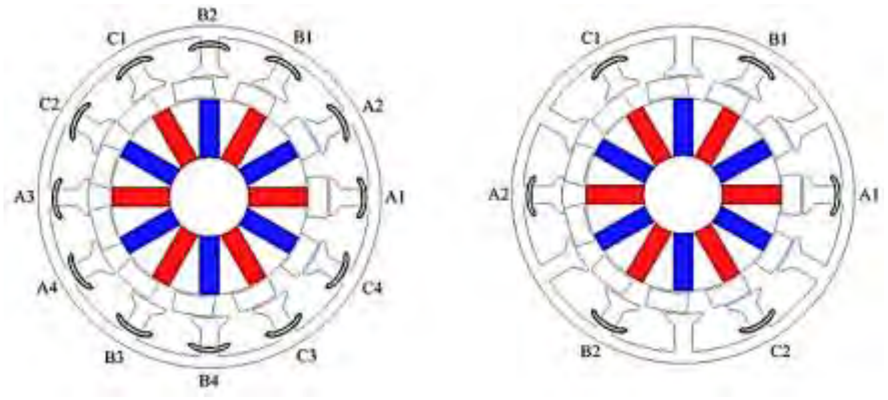
FEA outcomes indicate that for 12 tooth of outer stator and 12 PMs of inner stator DS-PMFS machines, the high torque density is generated in double-layer windings, but for 12 tooth of outer stator and 6 PMs inner stator DS PMFS machines, the high torque was achieved in the single-layer windings. Overall, the 12 outer stator teeth and 12 inner stator PM DS FSPM machines generate high torque densities and minimum torque ripples as compared to the 12 tooth of outer stator and 6 PMs of inner stator DS FSPM machines as publicized in Table 2.2.

Table 2.2: Performance of Ra DS PMFSM [100]

Ra DS MFSM / Performance	Single layer		Double layer	
	6PMs	12PMs	6 PMs	12PMs
Back emf (V)	4	5.9	3.88	6.75
Cogging torque (Nm)	1	0.02	1	0.02
Torque (Nm)	6.23	8.85	5.15	9.90
Power	505	505	510	505

Likewise, in 2016, another novel type of radial DS-PMSFM with single-layer and double-layer windings is established in [101] as shown in Figure 2.9. These machines have been optimized using ‘genetic algorithm’ (GA) by keeping the constant copper loss to achieve the maximum torque. The outcomes of these machines indicate that the DS-PMSFMs having the same number of PMs Poles with armature coils achieved the high torque, irrespective of single-layer or double-layer windings. Nevertheless, the single-layer winding DS-PMSFMs with the PMs poles half of that with armature coils have the good PM usage along with the highest ratio of torque to PM volume, and thus, are strong candidate for the cost sensitive applications. Further, a prototype of machine is established and tested to confirm the analyses [101].

Correspondingly, the investigation of radial DS PMSFM structures and operation principles are presented in [102]. The cross section of this 12S-10P DS PMSFM is given in Figure 2.10. In this machine, the flux linkage by means of PM can be varied by mechanically varying the locations of the PMs and armature winding stators, which can deliver the potential enhancements on the range of speed and torque densities. The proposed method is confirmed by three dimensional (3D) FEA and experiments on the prototype machines.



(a) (b)

Figure 2.9**:** Cross sections view of the 12S-11P DS-PMFSM (a) double-layer (b) single-layer [101]

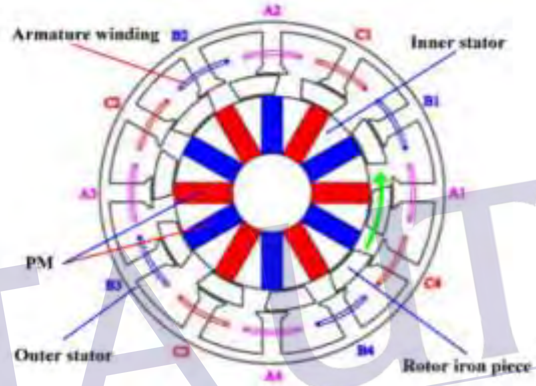


Figure 2.10**:** Cross section view of 12S-10P DS-PMFSM [102]

Moreover, the "magnetic gear effect" of the DS-PMFSM were studied in terms of air gap field harmonics based on simple MMF permeance model in 2016 [103]. The DS-PMSFM was found to be one type of magnetically geared machine in which the modulations of rotor iron parts to open-circuit PM and armature reaction fields are identical to those seen in the magnetic gear and traditional magnetically geared machine. In this article, finite element (FE) analysis validated the pole-pair numbers and rotational speeds of the air-gap field harmonics produced by the MMF-permeance model. In this machine, 93% higher torques generated in both the outer and inner air-gaps are contributed by the main harmonics with pole-pair numbers $(2i-1)p$ PM and $Nr\pm(2i-1)p$ PM, where (i = 1,2,3) [103]. The cross section view of 12S-10p DS PMFSM is shown in Figure 2.11.

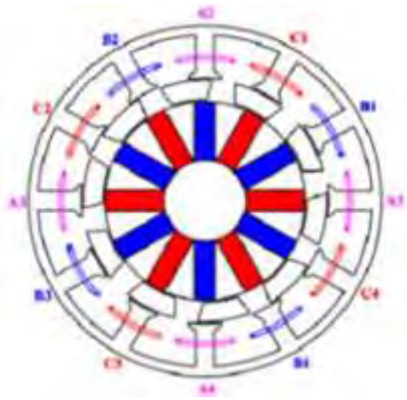
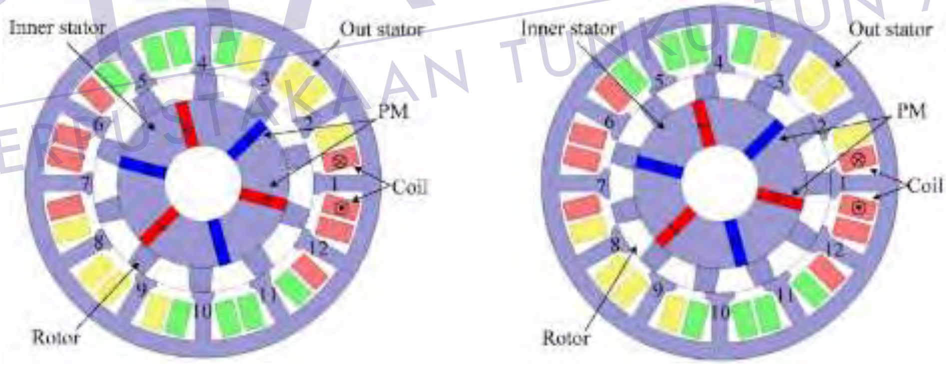


Figure 2.11: Cross-sections of 12S-10P DS-SFPM magnetic gearing [103]

Whereas, a new class of novel radial DS biased flux machine (DS BFMs) were suggested in [104]. In the latter examination, the number of coils is identified as similar to the number of the stator tooth. Two different structures of DS BFMs were suggested to illustrate the basic concept of machine having 12 stator poles, coupling with 10-rotor poles and 11-rotor pole respectively. The PMs and excitation sources for these machines were separately placed in inner and outer stator as shown in Figure. 2.12. So that, the appropriate circulation of electric and magnetic loading in both stators can be enhanced to increase the torque density.



(a) (b)

Figure 2.12**:** Proposed DSBFMs. (a) 12S-10P DSBFM (b) 12S-11P DSBFM [104]

In this machine, it is found that DS BFM with 11 rotor poles has the better performance than DS BFM with 10 rotor poles. So, the detailed analysis of DS BFM with 11 is presented in [104]. The simulation outcomes indicate that the suggested machine has the ability to produce high torque density, less torque ripple and satisfactory efficiency for higher torque and lower speed direct drive applications.

In 2016, DS-PMFSM ferrite-based machine was introduced to substitute an "internal permanent synchronous magnet (IPMSM)" motor for HEVs in [105] as shown in

Figure 2.13. The proposed in [105] machine was analysed using "frozen permeability method" (FPM). Further, it was confirmed from the analysis that the flux linkage reduction of coil is significant to increase magnetic saturation. Henceforth, a DS-PMFSM shows an appropriate performance in terms of coil flux reduction by the fact of decreasing magnetic saturation due to its unique configuration. Consequently, the suggested DS-PMFSM does had an improvement in performance of 6% and 3% relative to an IPMSM with NdFeB and an SRM with a super core even though using both specific silicon steel and ferrite PM.

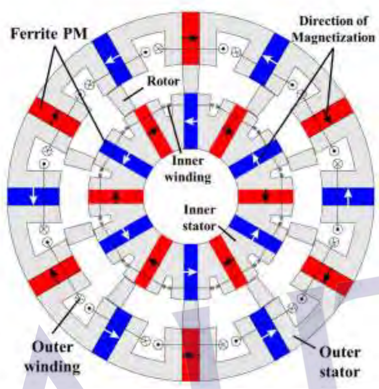


Figure 2.13**:** Cross-sectional diagram of DS-PMFSM proposed in [105]

Well ahead in 2017, another structure of radial DS-FSM with double air gaps is developed in [106]. The DS FSM is designed and confirmed using FEA method. The DS-FSM structure presented in [106] is shown in Figure 2.14.

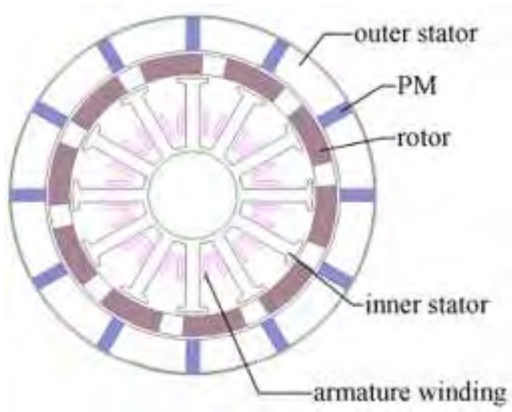


Figure 2.14**:** Radial field DS-FSM proposed in [106]

In this design, the PMs and armature coils were situated on outer and inner stators separately with extended stator areas. The findings of the analysis show that the DS-

REFERENCES

1. Cao, W., Mecrow, B. C., Atkinson, G. J., Bennett, J. W., & Atkinson, D. J. (2011). Overview of electric motor technologies used for more electric aircraft (MEA). *IEEE transactions on industrial electronics*, 59(9), 3523-3531.
2. Boglietti, A., Cavagnino, A., Tenconi, A., Vaschetto, S., & di Torino, P. (2009). The safety critical electric machines and drives in the more electric aircraft: A survey. *35th Annual Conference of IEEE Industrial Electronics*, Porto, pp. 2587-2594.
3. Bose, B. K. (2008). Power electronics and motor drives recent progress and perspective. *IEEE transactions on industrial electronics*, 56(2), 581-588.
4. De Lillo, L., Empringham, L., Wheeler, P. W., Khwan-On, S., Gerada, C., Othman, M. N., & Huang, X. (2009). Multiphase power converter drive for fault-tolerant machine development in aerospace applications. *IEEE Transactions on Industrial Electronics*, 57(2), 575-583.
5. Galea, M., Papini, L., Zhang, H., Gerada, C., & Hamiti, T. (2015). Demagnetization analysis for Halbach array configurations in electrical machines. *IEEE Transactions on Magnetics*, *51*(9), 1-9.
6. Sulaiman, E., Kosaka, T., & Matsui, N. (2011). High power density design of 6-slot–8-pole hybrid excitation flux switching machine for hybrid electric vehicles. *IEEE Transactions on Magnetics*, *47*(10), 4453-4456.
7. Sulaiman, E. B., Kosaka, T., & Matsui, N. (2012, September). Design study and experimental analysis of wound field flux switching motor for HEV applications. In *2012 XXth International Conference on Electrical Machines* (pp. 1269-1275).
8. Thomas, A. S., Zhu, Z. Q., Owen, R. L., Jewell, G. W., & Howe, D. (2009). Multiphase flux-switching permanent-magnet brushless machine for aerospace application. *IEEE Transactions on industry applications*, *45*(6), 1971-1981.

9. Sulaiman, E., Kosaka, T., & Matsui, N. (2012). Design optimization and performance of a novel 6-slot 5-pole PMFSM with hybrid excitation for hybrid electric vehicle. *IEEJ Transactions on Industry Applications*, *132*(2), 211-218.

10. Sanabria-Walter, C., Polinder, H., & Ferreira, J. A. (2013). High-torque-density high-efficiency flux-switching PM machine for aerospace applications. *IEEE journal of emerging and selected topics in power electronics*, *1*(4), 327-336.

11. Chai, F., Xia, J., Guo, B., & Cheng, S. (2008, June). Double-stator permanent magnet synchronous in-wheel motor for hybrid electric drive system. In *2008 14th Symposium on Electromagnetic Launch Technology* (pp. 1-5). IEEE.

12. Li, Y., Bobba, D., & Sarlioglu, B. (2016). Design and performance characterization of a novel low-pole dual-stator flux-switching permanent magnet machine for traction application. *IEEE transactions on industry applications*, *52*(5), 4304-4314.

13. Gandhi, A., & Parsa, L. (2016). Double-rotor flux-switching permanent magnet machine with yokeless stator. *IEEE transactions on energy conversion*, *31*(4), 1267-1277.

14. Zong, Z., Quan, L., & Xiang, Z. (2014, October). Comparison of double-stator flux-switching permanent magnet machine and double-stator permanent magnet synchronous machine for electric vehicle applications. In *2014 17th International Conference on Electrical Machines and Systems (ICEMS)* (pp. 234-239).

15. Melfi, M. J., Rogers, S. D., Evon, S., & Martin, B. (2006, September). Permanent magnet motors for energy savings in industrial applications. in *IEEE Transactions on Industry Applications*, vol. 44, no. 5, pp. 1360-1366, Sept.-Oct. 2008.

16. Matsuhashi, D., Matsuo, K., Okitsu, T., Ashikaga, T., & Mizuno, T. (2015). Comparison study of various motors for EVs and the potentiality of a ferrite magnet motor. *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, Hiroshima, 2014, pp. 1886-1891.

17. Boldea, I., Tutelea, L. N., Parsa, L., & Dorrell, D. (2014). Automotive electric propulsion systems with reduced or no permanent magnets: An overview. *IEEE Transactions on Industrial Electronics*, *61*(10), 5696-5711.

18. Zhu, Z. Q., Wu, Z. Z., Evans, D. J., & Chu, W. Q. (2014). A wound field switched flux machine with field and armature windings separately wound in double stators. *IEEE Transactions on Energy Conversion*, *30*(2), 772-783.
19. Chu, W. Q., Zhu, Z. Q., & Chen, J. T. (2013). Simplified analytical optimization and comparison of torque densities between electrically excited and permanent-magnet machines. *IEEE Transactions on Industrial Electronics*, *61*(9), 5000-5011.
20. Zhao, J., Lin, M., Jin, L., & Xu, D. (2015, September). Stator-flux-oriented vector control of hybrid excited axial field flux-switching machine. In *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)* (pp. 1-10).
21. Krenn, J., Krall, R., & Schmid, A. (2014, October). Comparison of torque-speed-characteristic of flux switching machines with permanent magnet excitation and hybrid excitation. In *2014 12th International Conference on Actual Problems of Electronics Instrument Engineering (APEIE)* (pp. 779-784).
22. Lin, H., Liu, X., Zhu, Z. Q., & Fang, S. (2011). Analysis and control of a dual-stator hybrid excitation synchronous wind generator. *IET electric power applications*, *5*(8), 628-635.
23. Tapia, J. A., Leonardi, F., & Lipo, T. A. (2003). Consequent-pole permanent-magnet machine with extended field-weakening capability. *IEEE Transactions on Industry Applications*, *39*(6), 1704-1709.
24. Chai, F., Xia, J., Guo, B., & Cheng, S. Zhang,G (2008, June). Double-stator permanent magnet synchronous in-wheel motor for hybrid electric drive system. in *IEEE Transactions on Magnetics*, vol. 45, no. 1, pp. 278-281, Jan. 2009.
25. Wang, Y., Cheng, M., Chen, M., Du, Y., & Chau, K. T. (2011). Design of high-torque-density double-stator permanent magnet brushless motors. *IET Electric power applications*, *5*(3), 317-323.
26. Khan, F., & Sulaiman, E. (2015, May). Design optimization and efficiency analysis of 12slot-10pole wound field flux switching machine. In *2015 IEEE International Magnetics Conference (INTERMAG)* (pp. 1-1).
27. Capponi, F. G., Borocci, G., De Donato, G., & Caricchi, F. (2015). Flux regulation strategies for hybrid excitation synchronous machines. *IEEE Transactions on Industry Applications*, *51*(5), 3838-3847.

28. Zhang, Q., Huang, S., & Xie, G. (2010). Design and experimental verification of hybrid excitation machine with isolated magnetic paths. *IEEE Transactions on Energy Conversion*, *25*(4), 993-1000.

29. Capponi, F. G., Borocci, G., De Donato, G., & Caricchi, F. (2015). Flux regulation strategies for hybrid excitation synchronous machines. *IEEE Transactions on Industry Applications*, *51*(5), 3838-3847.

30. Sulaiman, E. B., Kosaka, T., & Matsui, N. (2012, September). Design study and experimental analysis of wound field flux switching motor for HEV applications. In *2012 XXth International Conference on Electrical Machines* (pp. 1269-1275).

31. Di Barba, P., Bonislawski, M., Palka, R., Paplicki, P., & Wardach, M. (2015). Design of hybrid excited synchronous machine for electrical vehicles. *IEEE Transactions on Magnetics*, *51*(8), 1-6.

32. International Electrotechnical Commission. (2004). Rotating electrical machines–Part 1: Rating and performance. *Determination of Winding Temperature*.

33. Bouzidi, I., Bianchi, N., & Masmoudi, A. (2014). An approach to the sizing of electric motors devoted to aerospace propulsion systems. *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*.

34. Bouzidi, I., Masmoudi, A., & Bianchi, N. (2015). Electromagnetic/thermal design procedure of an aerospace electric propeller. *IEEE Transactions on Industry Applications*, *51*(6), 4364-4371.

35. Glass-Hooper, D. T. (1916). The electric control of large aeroplanes. *Flight*, *8*(51), 1118.

36. Ribeiro, R. L. A., Jacobina, C. B., Lima, A. M. N., & Da Silva, E. R. C. (2001, March). A strategy for improving reliability of motor drive systems using a four-leg three-phase converter. In *APEC 2001. Sixteenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No. 01CH37181)* (Vol. 1, pp. 385-391).

37. Barrero, F., Prieto, J., Levi, E., Gregor, R., Toral, S., Duran, M. J., & Jones, M. (2010). An enhanced predictive current control method for asymmetrical six-phase motor drives. *IEEE Transactions on Industrial Electronics*, *58*(8), 3242-3252.

38. Patel, V. I., & Wang, J. (2013, September). Assessment of 12-slot, 14-pole permanent magnet flux switching machine with hybrid excitation for electric vehicle application. In *2013 IEEE Energy Conversion Congress and Exposition* (pp. 5092-5099).

39. Somesan, L., Padurariu, E. and Viorel, I., 2013. Permanent Magnet Flux-Switching Machine, Optimal Design and Performance Analysis. *Advances in Electrical and Electronic Engineering*, 11(2), pp. 46–53

40. Fei, W., Shen, J., Wang, C., & Chi-Kwong Luk, P. (2011). Design and analysis of a new outer-rotor permanent-magnet flux-switching machine for electric vehicle propulsion. *COMPEL - The International Journal For Computation And Mathematics In Electrical And Electronic Engineering*, *30*(1), 48-61.

41. Sulaiman, Teridi, M., Husin, Z., Ahmad, M., & Kosaka, T. (2013). Investigation on Flux Characteristics of Field Excitation Flux Switching Machine with Single FEC Polarity. *Procedia Technology, 11*, 572-579.

42. Zhu, Z. Q., Zhou, Y. J., Chen, J. T., & Green, J. E. (2015). Investigation of nonoverlapping stator wound-field synchronous machines. *IEEE Transactions on Energy Conversion*, *30*(4), 1420-1427.

43. Galea, M., Gerada, C., & Hamiti, T. (2012, September). Design considerations for an outer rotor, field wound, flux switching machine. In *2012 XXth International Conference on Electrical Machines* (pp. 171-176).

44. Hoang, E., Ben Ahmed, A. H., & Lucidarme, J. (1997). Switching flux permanent magnet polyphased machines [J]. 7th European Conf. *Power Electronic and Applications*, *3*, 903-908.

45. Sanabria-Walter, C., Polinder, H., Ferreira, J. A., Jänker, P., & Hofmann, M. (2012, September). Torque enhanced flux-switching PM machine for aerospace applications. In *2012 XXth International Conference on Electrical Machines* (pp. 2585-2595).

46. Chen, J. T., & Zhu, Z. Q. (2009). Winding configurations and optimal stator and rotor pole combination of flux-switching PM brushless AC machines. *IEEE Transactions on Energy Conversion*, *25*(2), 293-302.

47. Deodhar, R. P., Pride, A., Iwasaki, S., & Bremner, J. J. (2013). Performance improvement in flux-switching PM machines using flux diverters. *IEEE Transactions on Industry Applications*, *50*(2), 973-978.

48. Pollock, C., Pollock, H., Barron, R., Coles, J. R., Moule, D., Court, A., & Sutton, R. (2006). Flux-switching motors for automotive applications. *IEEE Transactions on Industry Applications*, *42*(5), 1177-1184.

49. Hua, W., Cheng, M., Zhu, Z. Q., & Howe, D. (2008). Analysis and optimization of back EMF waveform of a flux-switching permanent magnet motor. *IEEE Transactions on Energy Conversion*, *23*(3), 727-733.

50. Zhu, Z. Q., & Chen, J. T. (2010). Advanced flux-switching permanent magnet brushless machines. *IEEE Transactions on Magnetics*, *46*(6), 1447-1453.

51. Awah, C. C., Zhu, Z. Q., Wu, Z. Z., Zhan, H. L., Shi, J. T., Wu, D., & Ge, X. (2015). Comparison of partitioned stator switched flux permanent magnet machines having single-or double-layer windings. *IEEE Transactions on Magnetics*, *52*(1), 1-10.

52. Zhu, Z. Q., Wu, Z. Z., & Liu, X. (2015). A partitioned stator variable flux reluctance machine. *IEEE Transactions on energy conversion*, *31*(1), 78-92.

53. Hoang, E., Ahmed, H. B., & Lucidarme, J. (1997, September). Switching flux permanent magnet polyphased synchronous machines. *in Proceeding of 7th European Conference on Power Electronics and Applications (EPE)*, vol. 3, pp. 903–908, 1997.

54. Yan, J., Lin, H., Huang, Y., Liu, H., & Zhu, Z. Q. (2009, November). Magnetic field analysis of a novel flux switching transverse flux permanent magnet wind generator with 3-D FEM. In *2009 International Conference on Power Electronics and Drive Systems (PEDS)* (pp. 332-335).

55. Chen, J. T., Zhu, Z. Q., Iwasaki, S., & Deodhar, R. (2010, September). A novel E-core flux-switching PM brushless AC machine. In *2010 IEEE Energy Conversion Congress and Exposition* (pp. 3811-3818).

56. Zhu, Z. Q., Chen, J. T., Pang, Y., Howe, D., Iwasaki, S., & Deodhar, R. (2008). Analysis of a novel multi-tooth flux-switching PM brushless AC machine for high torque direct-drive applications. *IEEE Transactions on Magnetics*, *44*(11), 4313-4316.

57. Walker, J. H. (1942). The theory of the inductor alternator. *Journal of the Institution of Electrical Engineers-Part II: Power Engineering*, *89*(9), 227-241.

58. Rauch, S. E., & Johnson, L. J. (1955). Design principles of flux-switch alternators [includes discussion]. *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*, *74*(3), 1261-1268.

59. Miller, T. J. E. (1993). Switched reluctance machines and their control. *Hillsboro, OH: Magna Physics*.

60. Pollock, C., & Wallace, M. (1999, October). The flux switching motor, a DC motor without magnets or brushes. In *Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No. 99CH36370)* (Vol. 3, pp. 1980-1987).

61. Pollock, C., Pollock, H., Barron, R., Coles, J. R., Moule, D., Court, A., & Sutton, R. (2006). Flux-switching motors for automotive applications. *IEEE Transactions on Industry Applications*, *42*(5), 1177-1184.

62. Bangura, J. F. (2006). Design of high-power density and relatively high-efficiency flux-switching motor. *IEEE Transactions on Energy Conversion*, *21*(2), 416-425.

63. Chen, J. T., Zhu, Z. Q., Iwasaki, S., & Deodhar, R. (2010, September). Low cost flux-switching brushless AC machines. In *2010 IEEE Vehicle Power and Propulsion Conference* (pp. 1-6).

64. Zulu, A., Mecrow, B. C., & Armstrong, M. (2010). A wound-field three-phase flux-switching synchronous motor with all excitation sources on the stator *2009 IEEE Energy Conversion Congress and Exposition*, San Jose, CA, 2009, pp. 1502-1509.

65. Zulu, A., Mecrow, B. C., & Armstrong, M. (2010). A wound-field three-phase flux-switching synchronous motor with all excitation sources on the stator. *IEEE transactions on industry applications*, *46*(6), 2363-2371.

66. Li, G. J., & Zhu, Z. Q. (2016). Hybrid excitation switched flux permanent magnet machines with hybrid magnets. *8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016),* Glasgow, 2016, pp. 1-6.

67. Hoang, E., Lecrivain, M., & Gabsi, M. (2007, September). A new structure of a switching flux synchronous polyphased machine with hybrid excitation. In *2007 European Conference on Power Electronics and Applications* (pp. 1-8).

68. Zeng, Z., & Lu, Q. (2019). A Novel Hybrid-Excitation Switched-Flux Linear Machine With Partitioned-Excitations. *IEEE Transactions on Magnetics*, *55*(12), 1-4.

69. Hua, W., Cheng, M., & Zhang, G. (2009). A novel hybrid excitation flux-switching motor for hybrid vehicles. *IEEE Transactions on Magnetics*, *45*(10), 4728-4731.

70. Owen, R. L., Zhu, Z. Q., & Jewell, G. W. (2010). Hybrid-excited flux-switching permanent-magnet machines with iron flux bridges. *IEEE Transactions on Magnetics*, *46*(6), 1726-1729.

71. Chen, J. T., Zhu, Z. Q., Iwasaki, S., & Deodhar, R. P. (2011). A novel hybrid-excited switched-flux brushless AC machine for EV/HEV applications. *IEEE Transactions on Vehicular Technology*, *60*(4), 1365-1373.

72. Zakaria, S. N. U., & Sulaiman, E. (2014, December). Magnetic flux analysis of E-Core hybrid excitation flux switching motor with various topologies. In *2014 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)* (pp. 95-98).

73. KOWALCZYK, M., VEZZINI, A., & GRZESIAK, L. (2013). Cylindrical double air gap motor for aerial applications. *choice*, *2000*(132.8), 150.

74. Ertugrul, N., Soong, W. L., Valtenbergs, S., & Chye, H. (2001, August). Investigation of a fault tolerant and high performance motor drive for critical applications. In *Proceedings of IEEE Region 10 International Conference on Electrical and Electronic Technology. TENCON 2001 (Cat. No. 01CH37239)* (Vol. 2, pp. 542-548).

75. Niu, S., Chau, K. T., Zhang, D., Jiang, J. Z., & Wang, Z. (2007, September). Design and control of a double-stator permanent-magnet motor drive for electric vehicles. In *2007 IEEE Industry Applications Annual Meeting* (pp. 1293-1300).

76. Lyu, S., Yang, H., Lin, H., Li, Y., & Zheng, H. (2019, May). Speed Range Extension of a Dual-Stator PM Machine Using Winding Switching Strategy. In *2019 IEEE International Electric Machines & Drives Conference (IEMDC)* (pp. 91-96).

77. Yulong, P., Feng, C., Jia, S., & Shukang, C. (2011, August). Design of the double-stator permanent magnet synchronous starter and generator used in electric vehicles. In *2011 International Conference on Electrical Machines and Systems* (pp. 1-4).

78. Qu, R., & Lipo, T. A. (2003). Dual-rotor, radial-flux, toroidally wound, permanent-magnet machines. *IEEE Transactions on industry applications*, *39*(6), 1665-1673.

79. Yeh, Y. H., Hsieh, M. F., & Dorrell, D. G. (2011). Different arrangements for dual-rotor dual-output radial-flux motors. *IEEE Transactions on Industry Applications*, *48*(2), 612-622.

80. Atallah, K., Calverley, S., Clark, R., Rens, J., & Howe, D. (2008, September). A new PM machine topology for low-speed, high-torque drives. In *2008 18th International Conference on Electrical Machines* (pp. 1-4).

81. Fan, Y., Jiang, H., Cheng, M., & Wang, Y. (2010, September). An improved magnetic-geared permanent magnet in-wheel motor for electric vehicles. In *2010 IEEE Vehicle power and propulsion conference* (pp. 1-5).

82. Rasmussen, P. O., Frandsen, T. V., Jensen, K. K., & Jessen, K. (2013). Experimental evaluation of a motor-integrated permanent-magnet gear. *IEEE Transactions on Industry applications*, *49*(2), 850-859.

83. Cheng, M., & Han, P. (2014, April). A dual-stator brushless doubly-fed induction motor for EV/HEV applications. In *2014 International Conference on Intelligent Green Building and Smart Grid (IGBSG)* (pp. 1-6).

84. Sourabh, S., & Parida, S. K. (2018, December). Design of a Novel U Shaped Dual Stator Brushless Doubly Fed Induction Machine. In *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)* (pp.1-6).

85. Hong, C., Huang, W., & Hu, Z. (2018). Design and Analysis of a High-Speed Dual Stator Slotted Solid-Rotor Axial-Flux Induction Motor. *IEEE Transactions on Transportation Electrification*, *5*(1), 71-79.

86. Wu, Z., & Ojo, O. (2009, September). Optimal magnetic design of the stator windings of dual stator winding squirrel-cage induction machines. In *2009 IEEE Energy Conversion Congress and Exposition* (pp. 256-261).

87. Upadhyay, P. R., & Rajagopal, K. R. (2006). FE analysis and computer-aided design of a sandwiched axial-flux permanent magnet brushless DC motor. *IEEE transactions on magnetics*, *42*(10), 3401-3403.

88. Ahmad, N., Khan, F., Ali, H., Ishaq, S., & Sulaiman, E. (2019). Outer rotor wound field flux switching machine for In-wheel direct drive application. *IET Electric Power Applications*, *13*(6), 757-765.

89. Abdollahi, M., & Mirsalim, M. (2019, February). Novel e-core double-stator two phase switched reluctance motor with segmental rotor. In *2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC)* (pp. 72-77).

90. Yang, S., Zhang, F., Zhang, Z., & Liu, H. (2018, December). Design of Double Stator Permanent Magnet Synchronous Motor With Low Speed Large Torque. In *2018 IEEE Student Conference on Electric Machines and Systems* (pp. 1-6).

91. Demir, Y., & Aydin, M. (2016). A novel dual three-phase permanent magnet synchronous motor with asymmetric stator winding. *IEEE Transactions on Magnetics*, *52*(7), 1-5.

92. Wang, Y., Sun, Y., Wang, Y., & Zhang, X. (2016, October). Simulation of dual-stator permanent magnet synchronous motor for electric vehicle. In *2016 IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)* (pp. 1430-1433).

93. Li, L., Li, D., & Qu, R. (2019, August). Novel Partitioned Stator Dual-PM Flux-Switching Permanent Magnet Machine with Mechanically Continuously Flux Adjusting Capability. In *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)* (pp. 1-4).

94. Zhu, Z. Q., Zhou, Y. J., & Chen, J. T. (2015). Electromagnetic performance of nonoverlapping stator wound field synchronous machine with salient pole rotor. *IEEE Transactions on Magnetics*, *51*(11), 1-4.

95. Khan, F., Sulaiman, E., & Ahmad, M. Z. (2017). Review of switched flux wound-field machines technology. *IETE Technical Review*, *34*(4), 343-352.

96. Sulaiman, E., Ahmad, M. Z., Haron, Z. A., & Kosaka, T. (2012, December). Design studies and performance of HEFSM with various slot-pole combinations for HEV applications. In *2012 IEEE International Conference on Power and Energy (PECon)* (pp. 424-429).

97. Zong, Z., Quan, L., & Xiang, Z. (2014, October). Comparison of double-stator flux-switching permanent magnet machine and double-stator permanent magnet synchronous machine for electric vehicle applications. In *2014 17th International Conference on Electrical Machines and Systems (ICEMS)* (pp. 234-239).

98. Evans, D. J., & Zhu, Z. Q. (2014). Novel partitioned stator switched flux permanent magnet machines. *IEEE Transactions on Magnetics*, *51*(1), 1-14.

99. Wu, Z. Z., Zhu, Z. Q., & Shi, J. T. (2015). Novel doubly salient permanent magnet machines with partitioned stator and iron pieces rotor. *IEEE Transactions on Magnetics*, *51*(5), 1-12.

100. Awah, C. C., Zhu, Z. Q., Wu, Z. Z., Zhan, H. L., Shi, J. T., Wu, D .Comparison of Partitioned Stator Switched Flux Permanent Magnet Machines Having Single-

and Double-layer Windings. *2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, 2015, pp. 1-5.

101. Awah, C. C., Zhu, Z. Q., Wu, Z. Z., Zhan, H. L., Shi, J. T., Wu, D., & Ge, X. (2015). Comparison of partitioned stator switched flux permanent magnet machines having single-or double-layer windings. IEEE Transactions on Magnetics, 52(1), 1-10.

102. Evans, D. J., Zhu, Z. Q., Zhan, H. L., Wu, Z. Z., & Ge, X. (2016). Flux-weakening control performance of partitioned stator-switched flux PM machines. *IEEE Transactions on Industry Applications*, *52*(3), 2350-2359.

103. Wu, Z. Z., & Zhu, Z. Q. (2016). Analysis of magnetic gearing effect in partitioned stator switched flux PM machines. *IEEE Transactions on Energy Conversion*, *31*(4), 1239-1249.

104. Sheng, T., & Niu, S. (2016, April). Design and analysis of novel double stator biased flux machines. In *2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)* (pp. 1-10).

105. Kim, D., Hwang, H., Bae, S., & Lee, C. (2016). Analysis and design of a double-stator flux-switching permanent magnet machine using ferrite magnet in hybrid electric vehicles. *IEEE Transactions on Magnetics*, *52*(7), 1-4.

106. Yu, D., Yunyun, C., & Linlin, Y. (2017, August). Design and comparison of double-stator and conventional flux switched permanent magnet motor. In *2017 20th International Conference on Electrical Machines and Systems (ICEMS)* (pp. 1-4).

107. Zhu, Z. Q., Zhou, Y. J., & Chen, J. T. (2015, March). Investigation of axial field partitioned stator switched flux machines. In *2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)* (pp. 1-7).

108. Li, Y., Kim, J. H., Leuzzi, R., Liu, M., & Sarlioglu, B. (2016, September). Novel 6-slot 4-pole dual-stator flux-switching permanent magnet machine comparison studies for high-speed applications. In *2016 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 1-8).

109. Syed, Q. A. S., Kurtović, H., & Hahn, I. (2017). *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, Sydney, NSW, 2017, pp. 1-5.

110. Kim, J. H., Li, Y., & Sarlioglu, B. (2016). Novel six-slot four-pole axial flux-switching permanent magnet machine for electric vehicle. *IEEE Transactions on Transportation Electrification*, *3*(1), 108-117.

111. Li, H., & Zhu, H. (2016). Design of bearingless flux-switching permanent-magnet motor. *IEEE Transactions on Applied Superconductivity*, *26*(4), 1-5.

112. Zhu, Z. Q., Pang, Y., Howe, D., Iwasaki, S., Deodhar, R., & Pride, A. (2005). Analysis of electromagnetic performance of flux-switching permanent-magnet machines by nonlinear adaptive lumped parameter magnetic circuit model. *IEEE Transactions on magnetics*, *41*(11), 4277-4287.

113. Hua, Wei, Ming Cheng, Z. Q. Zhu, and David Howe. "Analysis and optimization of back EMF waveform of a flux-switching permanent magnet motor." *IEEE Transactions on Energy Conversion* 23, no. 3 (2008): 727-733.

114. Hwang, C. C., Li, P. L., & Liu, C. T. (2012). Design and analysis of a novel hybrid excited linear flux switching permanent magnet motor. *IEEE transactions on magnetics*, *48*(11), 2969-2972.

115. Bash, Michelle L., and Steven D. Pekarek. "Modeling of salient-pole wound-rotor synchronous machines for population-based design." *IEEE Transactions on Energy Conversion* 26, no. 2 (2011): 381-392.

116. McCarty, F. B. (1987). *U.S. Patent No. 4,656,379*. Washington, DC: U.S. Patent and Trademark Office.

117. Zhao, J., Lin, M., & Xu, D. (2016). Minimum-copper-loss control of hybrid excited axial field flux-switching machine. *IET Electric Power Applications*, *10*(2), 82-90

118. Amara, Y., Vido, L., Gabsi, M., Hoang, E., Ahmed, A. H. B., & Lecrivain, M. (2008). Hybrid excitation synchronous machines: Energy-efficient solution for vehicles propulsion. *IEEE Transactions on Vehicular Technology*, *58*(5), 2137-2149.

119. Patin, N., Vido, L., Monmasson, E., Louis, J. P., Gabsi, M., & Lecrivain, M. (2008). Control of a hybrid excitation synchronous generator for aircraft applications. *IEEE Transactions on Industrial Electronics*, *55*(10), 3772-3783.

120. Chau, K. T., Li, Y. B., Jiang, J. Z., & Niu, S. (2006). Design and control of a PM brushless hybrid generator for wind power application. *IEEE Transactions on Magnetics*, *42*(10), 3497-3499.

121. Henneberger, G., HADJI, M. J., & Ciorba, R. C. (1994). Design and test of permanent magnet synchronous motor with auxiliary excitation winding for electric vehicle application. *Proceeding Of European Power Electronics Chapter Symposium*. pp. 645–649.

122. Fodorean, D., Djerdir, A., Viorel, I. A., & Miraoui, A. (2007). A double excited synchronous machine for direct drive application—Design and prototype tests. *IEEE Transactions on Energy Conversion*, *22*(3), 656-665.

123. Leonardi, F., Matsuo, T., Li, Y., Lipo, T. A., & McCleer, P. (1996, October). Design considerations and test results for a doubly salient PM motor with flux control. In *IAS'96. Conference Record of the 1996 IEEE Industry Applications Conference Thirty-First IAS Annual Meeting* (Vol. 1, pp. 458-463).

124. Gaussens, B., Hoang, E., Lécrivain, M., Manfe, P., & Gabsi, M. (2013). A hybrid-excited flux-switching machine for high-speed DC-alternator applications. *IEEE Transactions on industrial electronics*, *61*(6), 2976-2989.

125. Naoe, N., & Fukami, T. (2001, June). Trial production of a hybrid excitation type synchronous machine. In *IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No. 01EX485)* (pp. 545-547).

126. Geng, W., Zhang, Z., Jiang, K., & Yan, Y. (2014). A new parallel hybrid excitation machine: Permanent-magnet/variable-reluctance machine with bidirectional field-regulating capability. *IEEE Transactions on Industrial Electronics*, *62*(3), 1372-1381.

127. Wang, Y., Deng, Z., & Wang, X. (2012). A parallel hybrid excitation flux-switching generator DC power system based on direct torque linear control. *IEEE Transactions on Energy Conversion*, *27*(2), 308-317.

128. Hua, H., & Zhu, Z. Q. (2017). Novel partitioned stator hybrid excited switched flux machines. *IEEE Transactions on Energy Conversion*, *32*(2), 495-504.

129. Zhao, X., & Niu, S. (2017). Design and optimization of a new magnetic-geared pole-changing hybrid excitation machine. *IEEE Transactions on Industrial Electronics*, *64*(12), 9943-9952.

130. Lee, C. H. T., Chau, K. T., Ching, T. W., & Chan, C. C. (2018). Design and Analysis of Partitioned-Stator Switched-Flux Dual-Excitation Machine for Hybrid Electric Vehicles. *World Electric Vehicle Journal*, *9*(3), 40.

131. Yunyun, C., Yu, D., Jiahong, Z., Xijing, L., & Fangjie, L. (2018, April). Optimization and Performance Improvement of Multi-excitation Double-stator

Flux-switching Machine. In *2018 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD)* (pp. 1-2).

132. Yu, D., Yunyun, C., Jiahong, Z., Xijing, L., & Fangjie, L. (2018, April). Design and Performance Investigation of Double-side Hybrid Excitation Flux-switching Machine. In *2018 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD)* (pp. 1-2).

133. Hua, H., & Zhu, Z. Q. (2016). Novel parallel hybrid excited machines with separate stators. *IEEE Transactions on Energy Conversion*, *31*(3), 1212-1220.

134. Ilhan, E., Kremers, M. F. J., Motoasca, E. T., Paulides, J. J. H., & Lomonova, E. A. (2012, September). Sensitivity analysis for phase inductances in flux-switching PM machines. In *2012 XXth International Conference on Electrical Machines* (pp. 763-768).

135. Zhu, Z. Q., & Evans, D. (2014, October). Overview of recent advances in innovative electrical machines-With particular reference to magnetically geared switched flux machines. In *2014 17th International Conference on Electrical Machines and Systems (ICEMS)* (pp. 1-10).

136. Xiaohe, M., Rong, S., Jet, T. K., Shuai, W., Xiaolong, Z., Vaiyapuri, V., & Sivakumar, N. (2015, November). Review of high speed electrical machines in gas turbine electrical power generation. In *TENCON 2015-2015 IEEE Region 10 Conference* (pp. 1-9).

137. Vesterstrom, J., & Thomsen, R. (2004, June). A comparative study of differential evolution, particle swarm optimization, and evolutionary algorithms on numerical benchmark problems. In *Proceedings of the 2004 congress on evolutionary computation (IEEE Cat. No. 04TH8753)* (Vol. 2, pp. 1980-1987).

138. Hegerty, B., Hung, C. C., & Kasprak, K. (2009, November). A comparative study on differential evolution and genetic algorithms for some combinatorial problems. In *Proceedings of 8th Mexican international conference on artificial intelligence* (pp. 9-13).

139. Risticevic, M., Iles, D., & Moeckel, A. (2016, June). Design of an interior permanent magnet synchronous motor supported by the topology optimization algorithm. In *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)* (pp. 221-225).

140. Dyck, D. N., & Lowther, D. A. (1996). Automated design of magnetic devices by optimizing material distribution. *IEEE Transactions on Magnetics*, *32*(3), 1188-1193.

141. Byun, J. K., Hahn, S. Y., & Park, I. H. (1999). Topology optimization of electrical devices using mutual energy and sensitivity. *IEEE Transactions on Magnetics*, *35*(5), 3718-3720.

142. Im, C. H., Jung, H. K., & Kim, Y. J. (2003). Hybrid genetic algorithm for electromagnetic topology optimization. *IEEE Transactions on Magnetics*, *39*(5), 2163-2169.

143. Wang, Y., Jin, M. J., Fei, W. Z., & Shen, J. X. (2010). Cogging torque reduction in permanent magnet flux-switching machines by rotor teeth axial pairing. *IET electric power applications*, *4*(7), 500-506.

144. Iles-Klumpner, D., Risticevic, M., & Boldea, I. (2005, May). Advanced optimization design techniques for automotive interior permanent magnet synchronous machines. In *IEEE International Conference on Electric Machines and Drives, 2005.* (pp. 227-234).

145. Kim, D. H., Sykulski, J. K., & Lowther, D. A. (2009). The implications of the use of composite materials in electromagnetic device topology and shape optimization. *IEEE transactions on magnetics*, *45*(3), 1154-1157.

146. Choi, J. S., & Yoo, J. (2009). Structural topology optimization of magnetic actuators using Genetic algorithms and ON/OFF sensitivity. *IEEE transactions on magnetics*, *45*(5), 2276-2279.

147. Sulaiman, E., Kosaka, T., & Matsui, N. (2011, August). Parameter optimization study and performance analysis of 6S-8P permanent magnet flux switching machine with field excitation for high speed hybrid electric vehicles. In *Proceedings of the 2011 14th European Conference on Power Electronics and Applications* (pp. 1-9).

148. Bramerdorfer, G., Tapia, J. A., Pyrhönen, J. J., & Cavagnino, A. (2018). Modern electrical machine design optimization: Techniques, trends, and best practices. *IEEE Transactions on Industrial Electronics*, *65*(10), 7672-7684.

149. Li, Y., Bobba, D., & Sarlioglu, B. (2017). Design and optimization of a novel dual-rotor hybrid PM machine for traction application. *IEEE Transactions on Industrial Electronics*, *65*(2), 1762-1771.

150. Wang, Q., Niu, S., & Yang, S. (2017). Design optimization and comparative study of novel magnetic-geared permanent magnet machines. *IEEE Transactions on Magnetics*, *53*(6), 1-4.

151. Zhao, X., & Niu, S. (2017). Design and optimization of a new magnetic-geared pole-changing hybrid excitation machine. *IEEE Transactions on Industrial Electronics*, *64*(12), 9943-9952.

152. Han, W., Tran, T. T., Kim, J. W., Kim, Y. J., & Jung, S. Y. (2015). Mass ionized particle optimization algorithm applied to optimal FEA-based design of electric machine. *IEEE Transactions on Magnetics*, *52*(3), 1-4.

153. Sulaiman, E., & Kosaka, T. (2012, July). Parameter sensitivity study for optimization of field-excitation flux switching synchronous machine for hybrid electric vehicles. In *2012 7th IEEE Conference on Industrial Electronics and Applications (ICIEA)* (pp. 52-57).

154. Jusoh, L., Sulaiman, E., Omar, M., & Soomro, H. (2018). A Comparative Study of Single-tooth and Multi-tooth Stator of 4S-8P Permanent Magnet FSM for Electric Bicycle Application. *International Journal of Engineering & Technology*, *7*(4.30), 295-298.

155. Sulaiman, E., Kosaka, T., & Matsui, N. (2011, May). Design optimization of 12Slot-10Pole hybrid excitation flux switching synchronous machine with 0.4 kg permanent magnet for hybrid electric vehicles. In *8th International Conference on Power Electronics-ECCE Asia* (pp. 1913-1920).

156. Sulaiman, E., Kosaka, T., & Matsui, N. (2011, August). A novel hybrid excitation flux switching synchronous machine for a high-speed hybrid electric vehicle applications. In *2011 International Conference on Electrical Machines and Systems* (pp. 1-6).

157. Ahmad, M. Z., Sulaiman, E., & Kosaka, T. (2015, March). Optimization of outer-rotor hybrid excitation FSM for in-wheel direct drive electric vehicle. In *2015 IEEE international conference on mechatronics (ICM)* (pp. 691-696).

158. Ahmad, M. Z., Sulaiman, E., & Kosaka, T. (2015). Analysis of high torque and power densities outer-rotor PMFSM with DC excitation coil for in-wheel direct drive. *Journal of Magnetics*, *20*(3), 265-272.

159. Ahmad, M. Z., Sulaiman, E., Haron, Z. A., & Khan, F. (2014). FEA-based design study of 12-slot 14-pole outer-rotor dual excitation flux switching machine for

direct drive electric vehicle applications. In *Applied Mechanics and Materials* (Vol. 660, pp. 836-840). Trans Tech Publications Ltd.

160. Mazlan, M. M. A., Sulaiman, E., Ahmad, M. Z., & Othman, S. M. N. S. (2014, December). Design optimization of single-phase outer-rotor hybrid excitation flux switching motor for electric vehicles. In *2014 IEEE Student Conference on Research and Development* (pp. 1-6).

161. Sulaiman, E., Zakaria, S. N. U., & Kosaka, T. (2015, March). Parameter sensitivity study for optimization of single phase E-Core hybrid excitation flux switching machine. In *2015 IEEE International Conference on Mechatronics (ICM)* (pp. 697-702).

162. Newcome, L. R. (2004). Unmanned Aviation: A Brief History of Unmanned Aerial Vehicles; American Institute of Aeronautics and Astronautics. Inc.: Reston, VA, USA, 45-50.

163. Masson, P. J., & Luongo, C. A. (2005). High power density superconducting motor for all-electric aircraft propulsion. IEEE Transactions on Applied Superconductivity, 15(2), 2226-2229.

164. Rippel, W. (2007). Induction versus dc brushless motors. Tesla Motors Blog.

165. Kuang, Z., Zhao, T., & Cui, S. (2016). Five-phase permanent magnet synchronous motor drive for aircraft applications. *In 2016 UKACC 11th IEEE.International Conference on Control* (CONTROL) (pp. 1-6).

166. Hoffman, A. N. (2015). Tesla Motors, Inc. Strategic Management and Business Policy.

167. Fehrenbacher, J., Stanley, D. L., & Honchell, J. (2011). Electric motor & power source selection for small aircraft propulsion.

168. Sulaiman, E., Kosaka, T., & Matsui, N. (2014). Design and analysis of high-power/high-torque density dual excitation switched-flux machine for traction drive in HEVs. *Renewable and Sustainable Energy Reviews*, *34*, 517-524.

169. Sulaiman, E., Kosaka, T., & Matsui, N. (2011, May). Design optimization of 12Slot-10Pole hybrid excitation flux switching synchronous machine with 0.4 kg permanent magnet for hybrid electric vehicles. In *8th International Conference on Power Electronics-ECCE Asia* (pp. 1913-1920).

170. Nagoya, I. (2012). *Design Studies on Less Rare-Earth and High Power Density Flux Switching Motors with Hybrid Excitation] Wound Field Excitation for HEV*

Drives (Doctoral dissertation, School of Engineering, Department of Computer Science and Engineering, Nagoya Institute of Technology).

171. Zulu, A. (2010). *Flux switching machines using segmental rotors* (Doctoral dissertation, Newcastle University).

172. Yilmaz, M. (2015). Limitations/capabilities of electric machine technologies and modeling approaches for electric motor design and analysis in plug-in electric vehicle applications. *Renewable and Sustainable Energy Reviews*, 52, 80-99.